Planarizer

Final Design Review

Project Members:

Timothy Jain

tsjain@calpoly.edu

Eric Ramos

eramos24@calpoly.edu

Aaron Tran

atran189@calpoly.edu

Matthew Wimberley

wimberle@calpoly.edu

Mechanical Engineering Department

California Polytechnic State University

San Luis Obispo

Winter 2022

Prepared For:

Cal Poly Legged Robots Team

Statement of Disclaimer

Executive Summary

The Cal Poly Legged Robots team has been working on a 2 degrees of freedom leg for a quadruped robot. They need a way to constrain the motion of this leg to the sagittal plane with limited dynamic effects so that it can be tested properly. Furthermore, the horizontal and vertical positional data must be collected with fine resolution. Meeting with our sponsors from the Cal Poly Legged Robots team, we have determined their wants and needs and placed them into a Quality Function Decomposition (QFD). This helped guide our decision processes in determining how the functionalities of the planarizer will be enabled. We performed ideation methods such as brainstorming, sketching, and concept modeling in order to generate a myriad of ideas for this planarizer. Through controlled convergence, we created Pugh matrices and judged the results of those within a weighted decision matrix to determine the design direction. Our senior project team has determined that a boom and base planarizer mechanism is a viable solution for meeting the needs of the Cal Poly Legged Robots team. The planarizer consists of a pivot joint that rotates 360 degrees in the yaw axis, i.e, in a circular path. Additionally, it allows for rotation to control the pitch of the leg. This allows for two degrees of freedom in the x and y directions in the sagittal plane. We have procured all the necessary components for our ultimate assembly and spent many man hours in the Aero Hangar machining and modifying our parts for fitting. The methods of compensation to limit inertial and gravity effects of the boom have been calculated and been found to be negligible compared to the dynamic forces of the moving robot leg. Additionally, two encoders track the yaw and pitch of our planarizer and feed this information to our DAQ microcontroller stationed on our yoke. A complete, detailed report of our senior project begins below.

Table of Contents

List of Figures

List of Tables

1. Introduction

The Cal Poly Legged Robots Team is an organization at California Polytechnic State University that is currently developing a quadruped robot. The team was created around a senior project for developing a two degrees of freedom (DOF) robot leg that was started in Winter 2020, as well as a SURP project proposed by Charlie Refvem in Summer 2020. The planarizer is a continuation of this work, sponsored by the Cal Poly Legged Robots Team, and is expected to constrain a robot leg to a sagittal plane (refer to Figure 1 for context) and collect its positional data for testing.

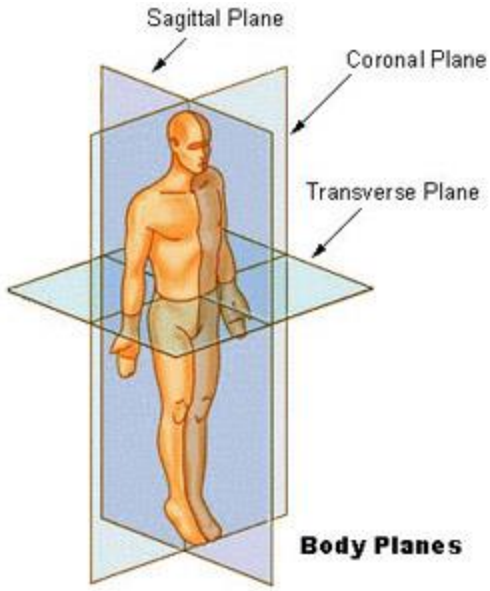


Figure 1. Planes of the human body; image provided by the National Institute of Medicine [1]

The goal of this Final Design Review is to present our team's ultimate prototype including our design choices and testing results. Following this introduction is the Background section which consists of understanding the customer's needs and wants, research of similar products, and technical research on these similar products to understand some of the design considerations. Afterwards, the Objective section clarifies what a potential user, namely the Cal Poly Legged Robots Team, hopes to see following project completion. The Concept Design section provides an overview of our ideation process and motivation for the design direction we chose. Our Final Design section covers our design and analysis on each of our subassemblies, safety, and further potential concerns. The manufacturing plan details how we manufactured all our components, with step-by-step instructions. The Design Verification Plan lists the various quantifying and qualifying tests we used to benchmark our finished prototype. The Project Management section details how we accomplished this goal. Finally, the Conclusion section provides an overall summary and reflection of our completed work.

2. Background

2.1 Customer Research

Gathering information about the customer involved getting to know the sponsors, since they are the key stakeholders. Thus, the sponsor meetings and Cal Poly Legged Robots team meetings were useful in this regard.

2.1.1: Sponsor Meetings

The sponsors assisting us in developing this planarizer are two professors from the Cal Poly Mechanical Engineering department and a third year Mechanical Engineering student: Professors Charlie Refvem and Dr. Siyuan Xing, and Mr. Cade Liberty. They are all members of the Cal Poly Legged Robots Team. They made it clear that the members of the team are our primary customer. By interviewing them, we were able to understand why they needed a planarizer. The purpose of the planarizer is mentioned by Professor Refvem, *"The planarizer constrains degrees of freedom of the leg; it allows the leg to be tested by itself."* They mentioned that the focuses are on testing vertical hopping, linear motion, and forward locomotion. Sagittal plane motion must be approximated as best as possible for these parameters. One particularly important specification they have provided is that the planarizer should collect data at a reasonably fine resolution. The types of encoders chosen will be critical for this step. Positional sensors are covered in Section 2.3.4. Furthermore, they mentioned that the system cannot induce large vibrations, as to avoid affecting the dynamics of the leg. They pointed to the open-source HOPPY model (described in detail in Section 2.2.1) as their inspiration for developing the leg dynamics and recommended that we borrow some elements of the planarizer from there as well. Because of this, we chose the boom and base model (justification given in Section 2.3.2.1). Some of their wants included making the planarizer collapsible and portable and the ability to be tested indoors and outdoors. In the second sponsor meeting, it was made clear that there will be no actuation occurring from the planarizer. Furthermore, it was specified that this planarizer will be used to test a single leg. Dr. Xing explained that initial testing on a single leg is critical to enabling the functionality of the whole quadruped. They suggested that we attach the encoders to the base of the boom, measuring the vertical and horizontal position of the leg relative to the sagittal plane. Ideally, there would be some form of serial communication between the base of the boom and the leg. Another ideal parameter they mentioned would be adjustability of the mount between the boom and the leg. They recommended that we have holes along the length of the boom to place the mounting plate on. The justification for this is that they do not want the planarizer to be redesigned if there are changes in the leg design. The current specifications of the leg are listed below in Table 1. The customer wants/needs are also summarized in Table 3 in Section 3.2.

Table 1: Current Cal Poly Legged Robots Leg Specifications

Parameter	Value
Leg Height	400 mm
Jump Height	800 mm
Leg Mass	1.25 kg

2.1.2: CP Legged Robots Team Meetings
The Cal Poly Legged Robots team is currently working on refining the dynamics of the leg. The leg is modeled as a SLIP (Single Leg Inverted Pendulum), which is based on the biomechanics of animal motion. This involves models in StateFlow and Simulink to accurately model the response of the leg in Stance phase (impacting the ground) and Flight phase (off the ground). We will continue to attend their biweekly meetings and will work closely with members of the team to ensure that these dynamic models are not disturbed while the planarizer is being utilized.

2.2 Product/Patent Research
Several robots that use a planarizer restraint mechanism were found and are covered below.

2.2.1: HOPPY
The HOPPY robot (depicted in Figure 2) is an open-source learning package developed by University of Illinois for the sake of robotics education [3]. It consists of a robotic leg that is attached to a rotating gantry with a fixed base. The significant length of this boom allows for the motion of the robotic leg to be approximated by a sagittal plane (shown in Figure 3), rather than a cylindrical one. Knee and hip motors control the actuation of the leg, while the 2 degrees of freedom are allowed via the gantry joint, allowing for pitch and yaw rotations. The robot package includes the simulator of the leg, scripts for leg dynamics, assembly instructions, as well as bill of materials. The positional data is collected via optical encoders. The Cal Poly Legged Robots team has relied heavily on the HOPPY model, and moving forward, we intend to receive inspiration from this model as well.

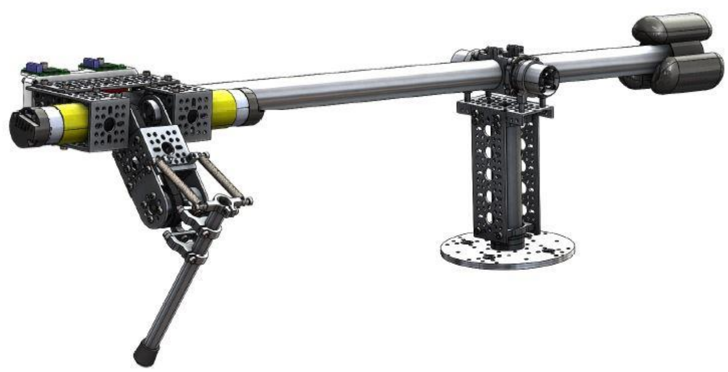


Figure 2: HOPPY boom-base assembly [3]

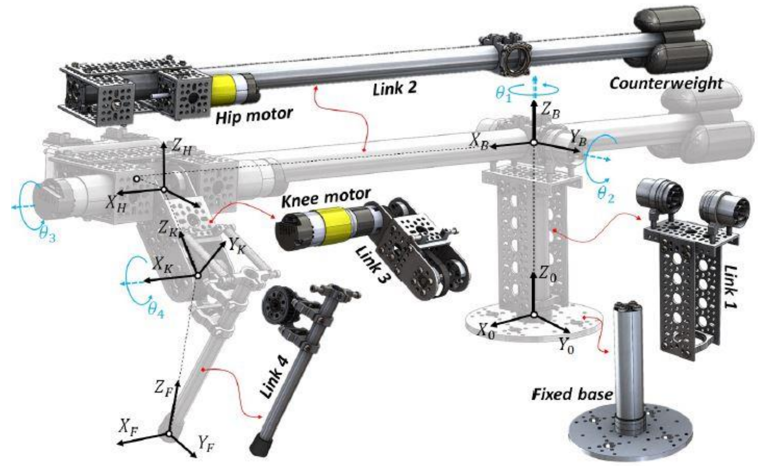


Figure 3. CAD model & exploded view of HOPPY assembly [3]

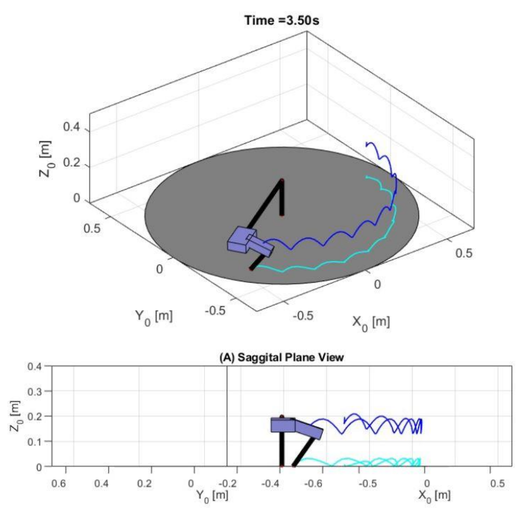


Figure 4. Sagittal approximation of leg dynamics [3]

2.2.2: BowLeg Hopper

The BowLeg Hopper, shown in Figure 4 below, is a a robot leg designed by The Robotics Institute of Carnegie Mellon University, with the goal of creating "a self-contained 3D hopper that can be driven by radio control." [4] The planarizer consists of a 2D gimbal mounted to the floor, a rotational joint in line with the robot's pitch axis, and an elastic rubber spring attached to the ceiling to reduce gravity effects. The choice of mounting the gimbal to the floor minimizes toe slippage during leg extension. The elastic rubber spring lessens the weight load placed on the robot leg by the planarizer by approximately two-thirds. The designers chose to use an elastic rubber spring as opposed to a counterweight to avoid increasing the rotational inertia of the planarizer.

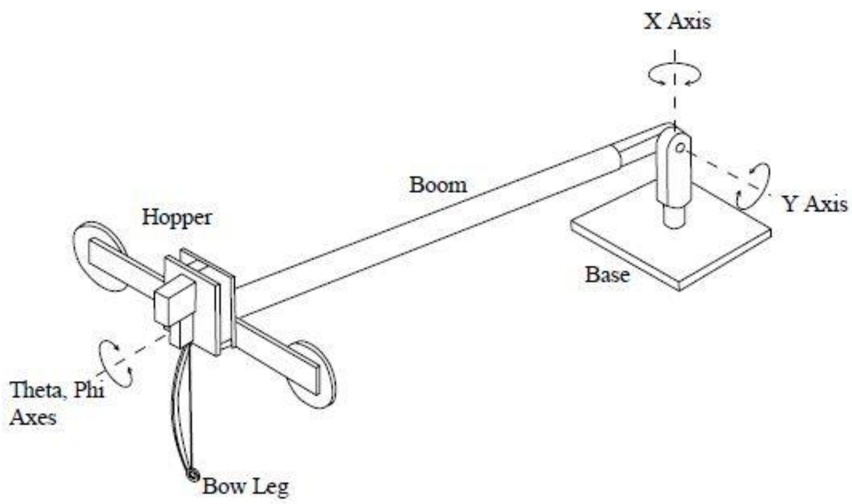


Figure 5. Bow Leg Hopper with an elastic rubber spring

2.2.3: Spring Flamingo

MIT developed Spring Flamingo to be a planar bipedal walking robot. The planarizer consisted of a boom arm, 2D gimbal, pitch rotation bearings at the robot's hip, wheels on the robot's feet to allow for toe slippage, potentiometers for data collection, and a counterweight to oppose the boom's gravitational effects. The control box making up the body of the flamingo can be seen below in Figure 5. During testing, the engineers discovered that the counterweight caused the boom to flex and decided to remove the counterweight [5].

Figure 6. Spring Flamingo, a planar bipedal robot developed by MIT

2.2.4: MABEL and Thumper

The University of Michigan developed the two-legged robot, Michigan Anthropomorphic Biped with Electronic Legs (MABEL) [6]. MABEL (Figure 6) is a large robot that received recognition for being the fastest bipedal robot with knees in 2011 and the world's first robot with a trip reflex. MABEL's planarizer consists of a simple boom arm and gimbal assembly connected to a floor to ceiling pole. As MABEL was designed to hold its own weight, gravitational compensation via an elastic spring or a counterweight was not necessary. To prevent damage due to falling, a catch was designed into the planarizer. The catch involved an internal hard stop to limit pitch but resulted in maintenance issues, as the robot had to be disassembled to access the hard stops. To collect data, the designers implemented absolute magnetic encoders, along with timing belts and pulleys to increase the resolution of the data. Another robot of similar size, Thumper, shown in Figure 7, used a similar planarizer setup and came into problems with flexure in the pole. This interfered with the robot's Z position sensing, interacted with the control system, and caused oscillations. Adjustments to the software and planarizer had to be made to reduce the oscillations [2].

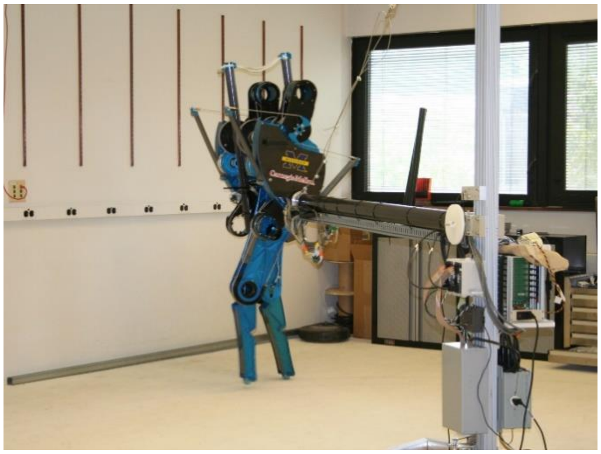


Figure 7. Michigan Anthropomorphic Biped with Electronic Legs (MABEL) attached to a boom

Figure 8. Thumper, a one-legged standing robot

2.2.5: Similar patents

Due to their nature, planarizers are not often patented; however, similar patents for products that have similar functions to components that we expect to implement in the planarizer may still prove to be useful to the design process. For this purpose, we have researched patents relevant to the boom arm, mount, and gimbal. Refer to Appendix A for the patents that we found.

2.3 Technical Research

In order to provide a solution that met our customer's wants and needs, we needed to understand the different types of planarizer mechanisms, certain design considerations with these mechanisms and how positional data collection of the leg dynamics would be enabled.

2.3.1: Restraint system considerations.

The methods of restraint systems for constraining motion were studied below. The primary ones include the boom and base, treadmill, planarizing assembly, and overhead gantry crane. These systems were outlined in Colett's thesis, and our findings are described below [2].

2.3.1.1: Boom and base

There are various ways that a robot's motion can be restrained. The restraint mechanism is necessary to sense the robot's orientation in space, catch it when it falls down, and maintain a 2D plane, which in our case is the sagittal plane. This range of motion can be seen in Figure 8 below, where a long arm, known as the boom, extends past the planarizer on the mount. Colett [2] describes these methods in detail. The most common method is by using a boom and base. The robot leg hops in a circular path and hops upwards along a spherical path, as seen in Figure 9. These are controlled by a joint at the base which allows for 360° rotation (circular path) and for pitch control (spherical path).

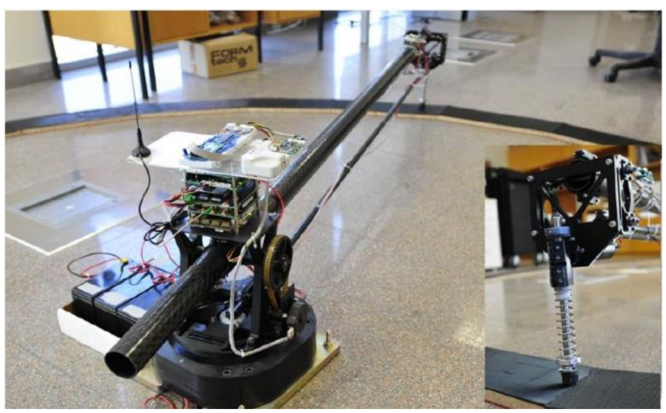


Figure 9. The carbon fiber boom utilized at Bilkent University [9]

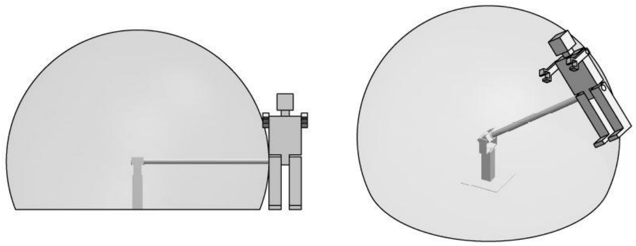


Figure 10. Preliminary sketch of person attached to boom, constrained to circular motion [2]

2.3.1.2: Treadmill

A treadmill (as shown in Figure 10 on the ARL Monopod II) can be utilized to constrain the linear motion of a robot leg. However, there tends to be inconsistencies when the foot contacts the treadmill. This is seen when humans are utilizing the treadmill, as the impact force varies from step to step. Furthermore, the belt of a treadmill accelerates with each step, so modeling this response proves to be contrived.

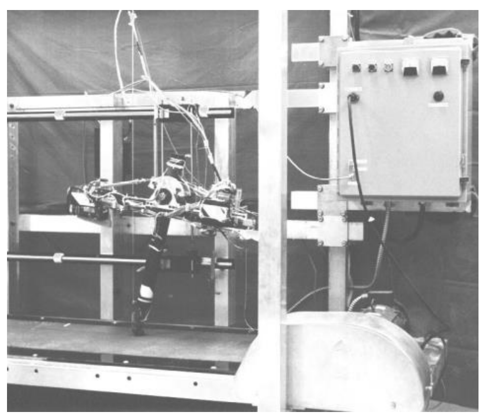


Figure 11. Primitive planarizer robot leg, mounted on treadmill to constrain to linear motion [2]

2.3.1.3: Planarizing Assembly

Another method utilized is the planarizing assembly as shown in Figure 11. This constrains the robot to a rectangular plane (translational vertical and horizontal), and uses linear bearings attached to rectangular tubes at the base. It approximates the sagittal plane well, since it is constrained to a rectangular plane. However, continuous motion needs to be provided to the robot leg, which may require the use of a treadmill.

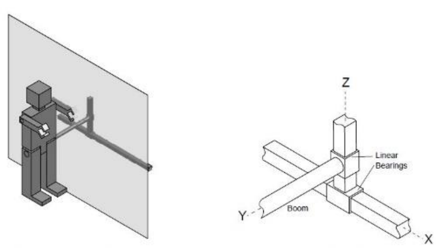


Figure 12. Contrained to rectangular plane [2]

2.3.1.4: Overhead Gantry Crane

The overhead gantry crane is installed permanently at the ceiling of a room. It is shown below in Figure 12:

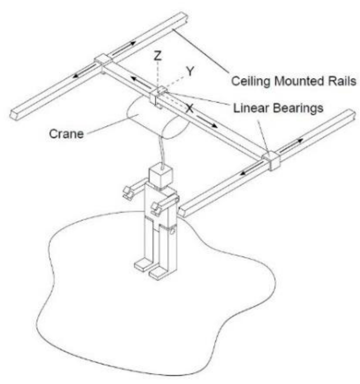


Figure 13. Crane Mounted Planarizer [2]

2.3.2: Design considerations

2.3.2.1: Pros/Cons Table

The advantages and disadvantages of each restraint mechanism is listed below in Table 2:

Table 2. Pros and Cons of Each Restraint Mechanism Considered

	Boom/Base	**Treadmill**	**Planarizing Assembly**	**Overhead Gantry**
Pros	• Sagittal plane approximation • 2DOF at gantry joint • Collapsible/portable	• Linear motion, easy dynamics	• Rectangular plane motion • Limited foot slip • No centrifugal forces	• Stable • Limited foot slipping

Cons	• Radial and transverse displacement of leg (foot slip)	• Discontinuities in forces of leg at impact • Variable belt acceleration • Bulky, large footprint	• No rotational DOF • Needs source of continuous motion	• Difficult to repair • Need large room/work space • Permanent

Based on these considerations, we decided the best move forward would be to utilize the boom/base assembly as our planarizing mechanism. The other mechanisms do not seem feasible due to the constraints that Cal Poly Legged Robots club has provided us. It would be difficult to approximate motion in the sagittal plane with the other options. Furthermore, the treadmill and overhead gantry require large workspaces and have large footprints (i.e, size, shape). They do not meet our customer's need of accessibility and portability. Since the Cal Poly Legged Robots club has received inspiration from the HOPPY model, we will remain consistent with their work and goals, which utilizes the boom/base mechanism.

2.3.2.2: Boom and Pivot Joint

The boom must be designed to be long enough so that we can approximate the spherical motion as 2D motion in the sagittal plane. An issue with the boom arm, however, is that flexing occurs. Thus, the structural integrity is compromised, and the chances of failure are increased. Furthermore, flexing adds unwanted vibration to the leg. As mentioned by Colett [2], these issues can be resolved by using a large diameter for the tube, a strong and stiff material such as carbon fiber, or cable reinforcements inside of the boom that increase the natural frequency of the first mode of vibration. Another consideration is the pivot joint at the base. The placement of this joint has an impact on how far the leg will slip. This is shown in Figure 13 below:

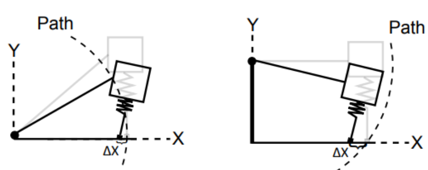
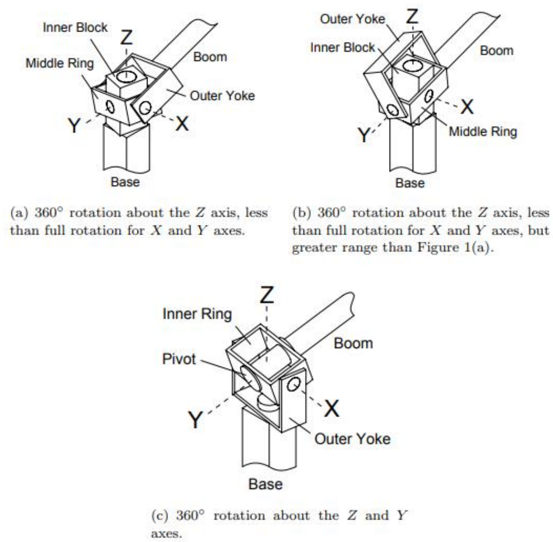


Figure 14. Spring mass system contrained to circular path [2]

This joint must allow for 360 degree yaw rotation as well as some motion in the x and y directions in order for the robot to move forward. Furthermore, the design must prevent sliding of the leg in the radial direction as well. Pivot joint design will be a focus area moving forward. Some pivot joint configurations are shown below in Figure 14. Collett recommends that the boom should not be offset relative to the vertical axis of rotation in order to approximate a straight line motion of the leg in the sagittal plane.



(a) 360° rotation about the Z axis, less than full rotation for X and Y axes.

(b) 360° rotation about the Z axis, less than full rotation for X and Y axes, but greater range than Figure 1(a).

(c) 360° rotation about the Z and Y axes.

Figure 15. Shoulder joint with boom attached mounted to a base [2]

2.3.2.3: Gravity Compensation

In order to reduce the effect of gravity due to the weight of the boom, certain measures can be taken to allow for the robot leg to jump to greater heights. One method is a spring or rubber cord that is attached to the ceiling, seen on the right side of Figure 16. It does not add much inertia to the boom, but it does need to be long enough so that weight compensation is still maintained through each hop of the robot. The BowLeg robot utilizes this method of compensation. Another method is by using counterweights on the end of the boom. It is effective in reducing the effect of gravity, however it adds considerable inertia to the boom, which can have considerable dynamic effects on the leg. Thus, the boom must be robust enough to accommodate these additional loads.

Figure 16. Boom with counterweight vs. Boom mounted to ceiling [2]

2.3.4: Data collection (DAQ) system

The customer has required the planarizer to be able to collect data at a high resolution. Thus, the positional data of the leg while in Stance and Flight states must be recorded. This can be done by using sensors such as potentiometers and/or encoders. Akihiro Sato from McGill University recommends using potentiometers that can measure the leg angle, and the roll and yaw angle of the boom. They rotate 360° and measure 340° [8]. Other boom and base mechanisms utilize optical encoders. Two encoders are placed at the pivot joint to measure the vertical and horizontal position of the leg with reference to the sagittal plane. The BowLeg robot utilizes these encoders at these locations, as well as a potentiometer at the mount to measure the angle of pitch of the boom [4]. Some recommendations we found from HOPPY were to use encoders with 12-bit resolution or 4096 counts per revolution [3]. Bilkent University even used incremental encoders that sampled at a rate at 500 Hz and a resolution of 8192 counts per revolution [9], however, the sponsors mentioned that we may want to sample at a rate of 200 Hz to start with. They also recommended that we chose an off the shelf encoder, such as the one shown in Figure 16 below:

Figure 17. High resolution DAQ system [10]

3. Objectives

3.1 Problem Statement

The members of the Cal Poly Legged Robot Team need a user-friendly restraint system to constrain a developmental robotic leg in the sagittal plane. The restraint system should collect data on the position of the robotic leg without significantly adding inertia and vibration to the dynamics of the leg. Additionally, data collection should have an appropriate sampling rate and resolution as to provide reasonably good data. This leg will go on to be part of a quadruped robot eventually, but the leg is currently in the early phase of design and is only being designed to work in a sagittal plane.

3.2 Stakeholders Wants and Needs

Table 3. Customer's Wants and Needs

Wants	Needs
• Collect data in real time • Use an out-of-the-box high resolution rotary encoder to track the position of the robotic leg. • Mount leg to testing boom using a standardized hole pattern. • House all circuits on base of planarizer • Use only one circuit board to collect data. • Ability to have circuit on planarizer tethered to a computer during entire testing time. • Avoid using a gear ratio to improve the resolution of the encoder. • Manage cables at base, so they are not tangled as the planarizer rotates around.	• Simulate robotic leg moving in forward direction. • No constraints or external forces in up and down direction • Collect high resolution data on the position of robotic leg. • Data collection speed of at least 200 Hz. • Be able to adjust planarizer with varying robotic leg specifications. • Make planarizer easy to move around. • Planarizer boom should be able to be broken down into pieces for storability. • Avoid resonance

3.3 Boundary Sketch

Our boundary sketch, found in Appendix B of this report, lays out the scope of this project as well the interaction between this project and the Cal Poly Legged Robots club's robotic leg. It outlines the systems which our senior project team is responsible for, and what the club is responsible for.

3.4 Quality Function Deployment (QFD)

The purpose of the Quality Function Deployment, found in Appendix C, is to quantify the customer needs and the engineering specifications. In analyzing and weighing the importance of these requirements, we were able to identify certain engineering aspects that we should focus on the most. We concluded that the top two customer needs were collecting high resolution data on the position of the leg and minimizing dynamic effects on the leg from the planarizer during simulation. To successfully fulfill the need of collecting high resolution data in an efficient manner, we would focus on increasing the sampling rate of our data acquisition system while reducing the upload time for it to be analyzed. To reduce the dynamic effects of the planarizer during simulation, we would focus on designing our boom to be lightweight and to reduce its vibration. This method can be applied to each of the remaining customer needs, such as portability, ease of use, and affordability.

3.5 Preliminary Engineering Specifications

Table 4. Engineering Specifications

Spec.#	Specification Description	Requirement or Target (units)	Tolerance	Risk*	Compliance**
1	Apparent Mass Increase	0.25 kg	Max	H	I
2	Apparent Mass Moment of Inertia Increase	0.25 kg-m^2	Max	M	I
3	Yaw Path Deviation	5 [deg/hop]	Max	L	T
4	Sampling Rate	200 Hz	Min.	M	I
5	Data Resolution (3DOF Linear Motion)	1 mm	Max	L	A
6	Cost	$1000	Max	M	A
7	Absolute Tip Deflection	0.01 mm	Max	M	A
8	Upload Time	15 seconds	Max	L	T
9	Assembly Time	20 minutes	Max	L	T
10	Allowable Leg Mass	1.25 kg	Min	M	A
11	Operating Leg Speed	1.3 m/s	Max	L	A

*Risk of meeting specification: (H) High, (M) Medium, (L) Low

** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to existing, (T) Test

3.5.1 Boom Mass
In the interest of minimizing the dynamic effects on the robot leg, we want to limit the mass of the boom to the best of our ability. This reduces the weight that the robotic leg would have to carry around during testing and the mass that the robot leg will have to try to move. An initial estimate that we have would be that the mass of the boom would be 10 % of the mass of the leg.

3.5.2 Boom Mass Moment of Inertia
In the interest of minimizing the dynamic effects on the robot leg, we want to limit the mass moment of inertia of the boom. The boom mass moment of inertia is determined by the geometry we select for it, as well as the boom mass. Our initial estimate is that this value for mass moment of inertia will be 10% of the mass moment of inertia of the leg evaluated about the boom post. We foresee the boom being the largest contributor to the rotational inertia of the planarizer, so it will be the main point of focus for reducing rotational inertia.

3.5.3 Yaw Path Deviation
Since we want to approximate movement in the sagittal plane to the best of our ability, we are setting a yaw path deviation limitation. We have defined this parameter as the degrees about the boom post that the robot leg would travel in a single hop when viewed from the top view. This is equivalent to the yaw angle.

3.5.4 Sampling Rate
The sampling rate is defined as the rate at which data will be collected. The sponsor has requested that this be at least 200 Hz to prepare the testing for a frequency analysis. They suspect that a boom design would result in a natural frequency of around 100Hz and want to ensure that they can test past it.

3.5.5 Data Resolution
Data resolution is defined as the smallest measurable unit of our data collections. As we are interested in tracking the position of the robot leg, we have designated the resolution to be 1 mm at the very largest for measuring the robots linear forward and vertical motion. For a boom-base assembly, we would account for all three linear dimensions of motion. Presumably, for a boom-base assembly, we would be measuring the polar and azimuth angle, and convert from the associated spherical coordinates to linear xyz-coordinates. The 1 mm resolution refers to being able to measure a 1 mm displacement in any direction. We hope to obtain as fine a resolution as possible. The goal set has been somewhat arbitrarily chosen and will be reconsidered upon further research.

3.5.6 Cost
Cost will include all expenditures regarding building the planarizer. We foresee that this will be spent mostly on materials, such as the encoder and the DAQ.

3.5.7 Absolute Tip Deflection
In the interest of collecting accurate data, we want to limit the boom tip deflection caused from bending. To evaluate this, we will measure the amplitude of the tip deflection due to the robot leg.

3.5.8 Upload Time
The initial plan was to bulk upload data, so a 15 second time limit for this was set as a requirement; however, to ensure a good user experience, we want to make sure that any data collected is uploaded and read in real time on a standby computer connected to our data acquisition system. Refer to 5. Final Design for more details.

3.5.9 Assembly Time
The sponsors have requested that we make the planarizer collapsible. To assist with the overhead of assembling and disassembling the product, we want to minimize the time it takes to put the planarizer back together.

3.5.10 Allowable Leg Mass
As the sponsors may be testing different sized robot legs, we want to be able to accommodate a wide range of masses. The estimation we have been provided so far for the mass of the robot leg they expect to test first is 2.5 kg. We foresee that testing smaller masses may be problematic as we think that the dynamic effects of the planarizer become more significant when compared to the dynamics of a smaller robot leg. To be safe, we will try to at least accommodate a robot half the weight of the proposed number.

3.5.11 Operating Leg Speed
The sponsors have first specified that the planarizer must be able to test a leg running up to 2 m/s. We do not foresee any issues with the leg running slower than this, but faster speeds may result in more boom flexure, larger yaw path deviation, and other effects we may not have considered. After secondary meetings with our sponsors, they told us the 2 m/s threshold is not necessary, as its running speed may be closer to 0.4 m/s, depending on the final size. Most importantly the leg must be stable with innocuous vibration.

4. Concept Design
Our concept design process consists of functional decomposition, concept ideation, concept modeling, and controlled convergence. This allowed us to determine the design direction of the planarizer and determine a final concept. The rest of this section will discuss the details of each of these parts.

4.1 Functional Decomposition
To first understand what to design and ideate for, we performed a functional decomposition for the planarizer. This process involved identifying the function, subfunctions, and attributes of the planarizer, allowing us to focus on specific parts to design for. The primary function of the planarizer is to allow testing of the robot leg. Underneath that primary function are four secondary functions. The first secondary function we focused on was collecting positional data. The sponsors indicated that for this necessary function, it would be convenient to store and upload data onto an SD card. The data must be uploaded to a computer and be of fine resolution. Our choice of encoders is dependent on a sampling rate of at least 200 Hz, and must provide a resolution within 1 mm. Another secondary function is that the planarizer must provide a user-friendly experience. This means that the power supply must be accessible, the planarizer needs to be portable and easily storable, and it should be versatile. This means accommodating different legs with different sizes, masses, and operating speeds. An additional secondary function is that the planarizer must limit dynamic effects. Most importantly, we hope to accomplish this by limiting motion to the sagittal plane. Another subfunction under this secondary function is that it should limit foot slipping. This means that as the robot contacts the ground, the robot

should not slide radially or tangentially from its landing point. Vibrational effects must also be limited. In this sense, we are referring to the fact that the planarizer frequency should not resonate with the natural frequency of the leg, otherwise permanent damage to the system is a major possibility. The planarizer should not inhibit the movement of the leg. This could be possible if the weight of the planarizer is significant compared to the weight of the leg, which would prevent the robot leg from moving in the circular path smoothly. Also, the inertial effects need to be limited. The purpose of the planarizer is to test a robot leg's operation as if it were acting by itself. The planarizer simply helps it do that. Adding unnecessary inertia would make the robot leg work harder than it needs to in order to move itself around. As a result, minimizing the inertia will be a significant part of the planarizer's design. The last secondary function we focused on was protecting the leg from damage. In this, we are referring to preventing electrical surges due to the battery. An additional consideration needed to be made is that the impact of the leg hitting the ground should not be increased due to the planarizer. The results of our functional decomposition can be seen in Appendix E.

4.2 Concept Ideation

Our team utilized the brainstorming method in order to determine solutions for different needs that the Cal Poly Legged Robots has specified. The needs that we focused on creating ideas for are listed below:

1. Constraining the motion of the leg to the sagittal plane
2. Limiting the amount of inertia and vibration
3. Collapsibility/portability.

We believe that these are the needs that affect the overall architecture and design of the planarizer the most, which is why we are giving all our concept ideation attention to them. The other needs are features that we believe we can address once the form factor of the planarizer has been determined. We drew concept sketches for these ideas on a whiteboard during our brainstorming ideation session, and these are shown in Appendix D: Ideation Processes. We focused on drawing sketches of ideas that met each need. Based on these sketches, we combined our ideas for meeting each need into concepts. Figures 17 through 24 depict the top concepts that we came up with. Furthermore, ideation models of these top concepts constructed from foamboard, and popsicle sticks are displayed in Appendix D.

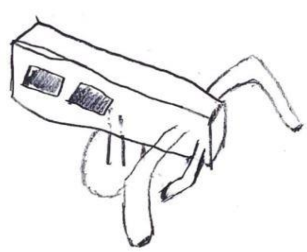


Figure 18: Design 1

Figure 18 (Design 1) illustrates a boom-base model with "training wheels" on the side. L-bars are attached to remove the risk of tipping, but this adds more mass outside the axis of rotation, increasing the bending stress at the tip of the boom.

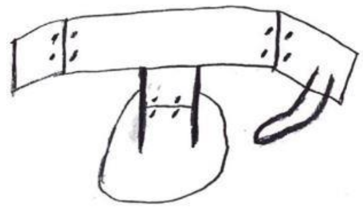


Figure 19: Design 2

To make a more portable model, the boom in Figure 19 (Design 2) is given hinges on both sides of the base and a hinge from the base to the boom. This allows the planarizer to fold inwards so that it is compact and can be stored easily.

Figure 20: Design 3

Figure 20 (Design 3) displays a boom-base planarizer which uses a cord to allow for overhead restraint of the leg. Overhead restraint is useful in keeping the robot leg stable with its gait, because it prevents it from tipping over due to adversities such as excessive foot slippage. This allows for more accurate data resolution.

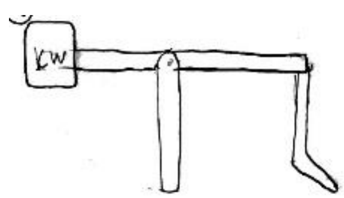


Figure 21: Design 4

Figure 21 (Design 4) displays a boom-base planarizer with a counterweight at the end. This is similar to the HOPPY robot as described above in Section 2.2.1. The counterweight provides a method of gravity compensation due to the weight of the boom. It reduces the effective weight of the boom “felt” by the leg, allowing the leg to hop in longer strides (greater yaw path deviation).

Figure 22: Design 5

The idea for the planarizer in Figure 22 (Design 5) is to constrain the space required to test the robot. A robot leg is hung from a cross-post and moves with the small treadmill. The treadmill is used to match the speed of the robot leg so that each stride is contacting with a consistent gait, allowing for data to be accurately collected. Although the testing space is small for this configuration, it is not easily storable.

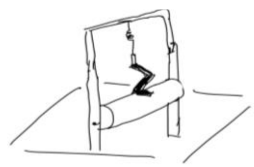


Figure 23: Design 6

In Figure 23 (Design 6), the robot leg is constrained from above by a spring. The robotic leg is placed above a freely rotating cylinder with a low rotational inertia. The robot leg then rotates the cylinder under its own power. The rotational speed of the cylinder is then tracked using an angular encoder.

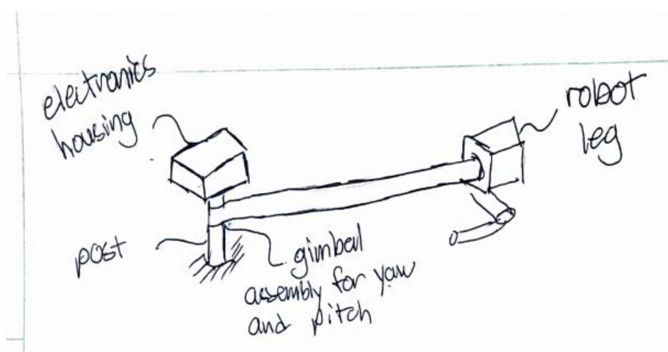


Figure 24: Design 7

In Figure 23 (Design 7), the planarizer consists of a simple boom and base. It has a box for electronic housing just above the post, and a gimbal assembly placed at the post to allow for yaw and pitch. In this concept, the robot leg would be free to pitch about the boom via a bearing placed at the mounting point.

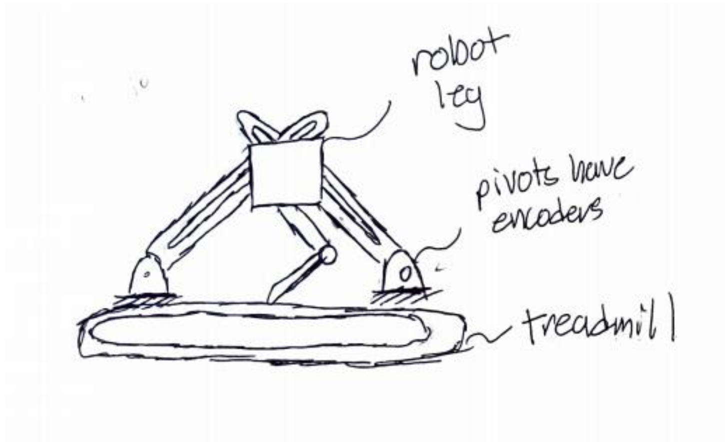


Figure 25: Design 8

In Figure 24 (Design 8), the planarizer incorporates a two-bar linkage and a treadmill. The two links are slotted to allow for a sliding pin connection to the robot. This would constrain the robot to a 2D plane. Of all the other top designs, this is the only one to perfectly constrain the robot to the sagittal plane, whereas the rest require an approximation. To account for the limited forward and backward movement that the robot leg would have due to a two-bar linkage, a treadmill would also be necessary. This would ensure that the robot leg could run for long enough to reach a steady state gait.

4.3 Controlled Convergence

To narrow our final decision for our concept model, we focused on the function of our base, ease of assembly, and compactness. Besides the designs listed above, we also considered a rectangular planarizer, as shown in Figure 11 in Section 2.3.1.3. It is shown below for reference.

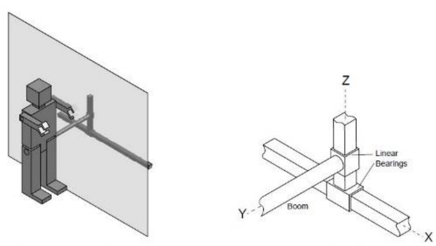


Figure 26: Contrained to rectangular plane [2]

We decided not to use this type of planarizer because it would be difficult to provide continuous motion. We would need to involve a treadmill, which would be costly and introduce other dynamic effects. According to the paper from Collett [2], the impact of the robot leg landing and jumping would cause a significant amount of variation in the treadmill speed. To account for this, much more thought must be put into the velocity control of the treadmill. We also believe that gathering data and syncing the robot speed with the treadmill would be more complex than is necessary. Additionally, we do not believe that including a treadmill into the design would be good for the collapsibility/storability of the overall assembly.

Our individual decisions for each design choice are laid out in our Pugh matrices in Appendix F and the same for our complete decision matrix in Appendix G. We each conceived at least 5 concept sketches, which were based on the ideation models that were constructed from foam board, popsicle sticks, and glue (shown in Appendix D). Each sketch was rated against each other according to several criteria which represented a different function or characteristic of our planarizer. They were graded on a plus, minus, or zero (S) scale. Some of these criteria include boom mass, yaw deviation, assembly time, boom tip deflection, boom vibration, portability, catch mechanism, protects encoders, "wow" factor, sagittal approximation, affordability, and the limiting of inertial effects. Based on the verdict of the Pugh matrices, each team member placed their two best concept sketches into our decision matrix. These concept sketches are Designs 1-8 as specified in Section 4.2. Here, we gave different customer specifications and design considerations weights as calculated in our QFD in Appendix C. This calculation takes into account the importance of each criteria to meeting our customer's needs. The criteria we judged each of our concept sketches against are listed as follows: apparent mass increase, apparent mass moment of inertia increase, path deviation, cost, data quality, assembly time, allowable mass, and operating speeds. Each design was scored on a scale from 1-5 on how well it met the customer's specification. Then, the score was multiplied by the relative weighting of importance of the criteria. We placed the greatest weighting on the apparent mass increase and data quality. If the apparent mass increase is less, than the design was scored higher. This criteria is important in order to ensure that the planarizer limits dynamic effects to the leg. The data quality is an important specification as mentioned by the sponsors, so that the positional data of the leg is accurate and can ensure smooth and successful operation of the quadruped in the future.

The result we obtained from this decision matrix process is a boom-base model. This would have the best form factor, as it provides the greatest versatility and portability while remaining inexpensive. There is a small sacrifice in that it will require approximating the sagittal plane, but we believe that we can design a fairly accurate approximation into the system by having a long enough boom. This is reflected in the decision matrix, as Design 7 and Design 3 performed the best. The key difference between these designs is Design 3 has a cord designed into it to act as a catch mechanism. This unfortunately, would require an extended post or ceiling attachment, which would reduce the portability of the planarizer. However, a catch mechanism is a customer requirement. Accordingly, we will continue to look for ways to implement a catch mechanism, leaving the method in Design 3 as a last resort. As of now, we continue with Design 7 as our chosen concept. The reasons why we did not choose the other of the top 8 designs reside primarily in the added inertia, instability, and/or portability. The light robot leg makes it difficult to justify adding any mass to the system, which is why all the features that Designs 1, 2, and 4 had to be ruled out. For Design 5 and Design 6, we believe that the robot leg would be unstable, as in it would not be able to stay in the plane we want it to. There does not seem to be a mechanism integrated into the designs that would restrict the robot leg to just moving forward or vertically. This is problematic, as we also believe that both designs would be costly and difficult to collapse and store. We would want to stay away from adding any features that would make this issue worse.

4.4 Final Concept

As discussed above, we chose Design 7. It is the most similar to the HOPPY model as referenced in Section 2.2.1, however it does not include the counterweight. This is promising, as it affirms what the sponsors suggested would be the best course of action and is in line with what has been done in the past, according to our research. The concept Solidworks CAD models of Design 7 are shown below. Pitch is controlled by a pin connection that goes through the boom and pivot connector as shown in Figure 27. The pin connection was done to provide the concept of controlling pitch in action but is not necessarily the connection we intend to use. Moving forward, we look to receive inspiration from HOPPY's pitch joint, which is controlled by two bearings as shown in Figure 29 [3]. Yaw is controlled by two bearings that rotate around the central pole as shown in Figure 30. The shafts are connected to rectangular vertical plates which attach the bearing assembly to the pivot connection.

Figure 27: Concept CAD Model

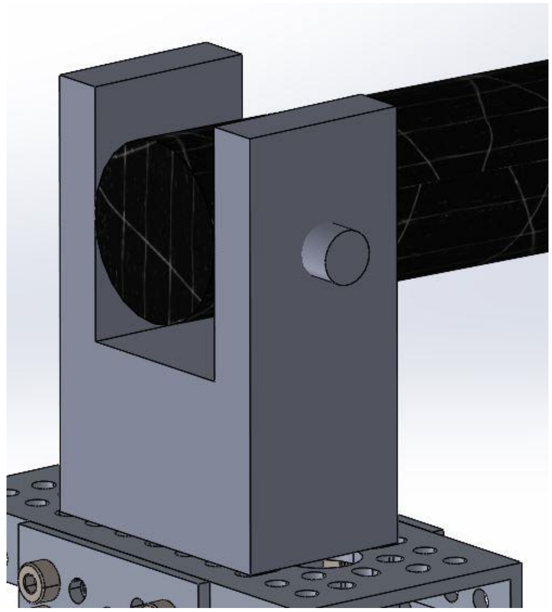


Figure 28: Pin connection through boom and base to allow for pitch motion

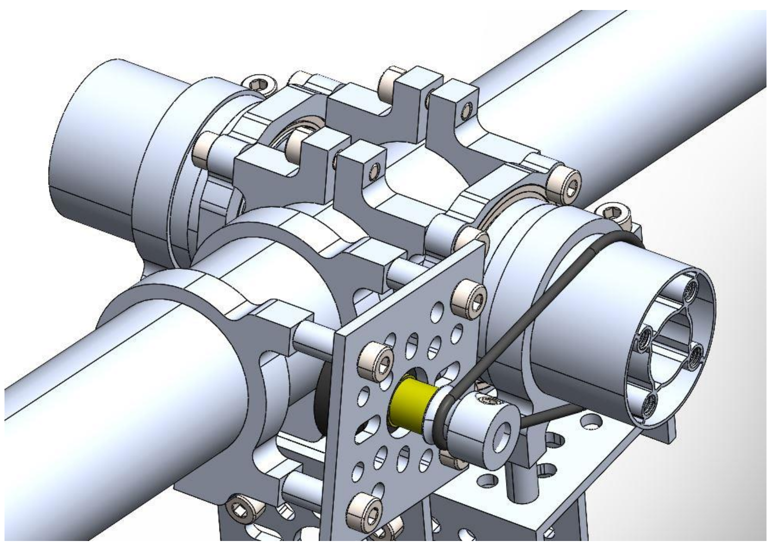


Figure 29: Pitch motion allowance mechanism on HOPPY robot [3]

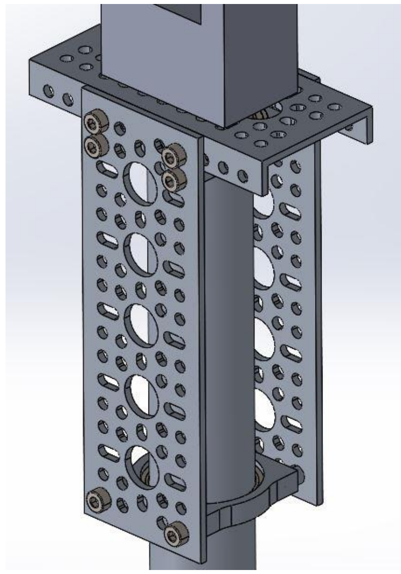


Figure 30: Close up of bearings configuration on base post that allow for yaw motion of planarizer

The concept prototype was constructed using 40” long PVC pipe with an inside diameter of 3/4”. Holes were drilled into the PVC boom, and a 3/8” wooden dowel was placed through it. This dowel was also placed through a post cap connector which normally is used for fence posts. This connector acted as the pivot for allowing pitch control. The connector is attached to the base post via an iron flange, and the base post is grounded with another iron flange. Unfortunately, the functionality of yaw was not allowed with this configuration due to limitation in access to a hole saw to drill holes in square plates, in which the bearings that rotate about the base post would be placed through. However, this motion can be simulated by one of the team members rotating the assembly while actuating the pitch motion.

Figure 31: Concept prototype of boom-base configuration of Design 7

4.5 Supporting Analysis

One of the main design challenges we foresee moving forward with the boom-base system is minimizing the dynamic effects of the planarizer. In preparation for this, we have some hand calculations underway for trying to determine the effect of the planarizer on the robot leg. The progress so far is shown in Appendix J. We do note, however, that we believe the analysis done so far is somewhat flawed. This is discussed at the end of the hand calculations. In short, the results of the calculation suggest that a planarizer with negligible inertia will result in the robot leg being incapable of moving. We do not believe this is a valid statement, so we will continue to refine our analysis and attempt to determine the dynamic effects. Aside from the decoupled equations presented in the appendix, we are also interested in determining an apparent mass and apparent mass moment of inertia increase due to the planarizer, as well as other metrics that we can use to define how well the spherical movement given by the planarizer matches a sagittal approximation. No calculations for this have been done thus far, but this is the plan as far as technical analysis goes.

4.6 Design Risks and Hazards

Our planarizer is fortunate to have few safety hazards. The risk and hazards checklist is shown in Appendix H: Design Hazard Checklist. The only potential for trouble stems from our use of electronics, where we plan to use a battery. This battery may overheat and cause a fire in the worst-case scenario, but we find this unlikely to happen. We plan to minimize this risk by capping our battery voltage at around 9 volts and placing terminal covers to eliminate the possibility of the battery short-circuiting. Additionally, the user will need to stay a safe distance away from the circular path in which the boom travels about when the planarizer is in operation.

5. Final Design

This section highlights the final design of our planarizer, as shown in Figure 32. We are implementing a boom-base model similar to HOPPY (Figure 2) towards reaching our sponsor's goals. It covers our thoughts and analysis for each subassembly of our complete system, as well as safety considerations, a cost analysis for each component of every subassembly, and lastly, remaining concerns on our design.

Figure 32: Full planarizer assembly with robot leg attached

5.1 Engineering Specifications Update

After speaking with the sponsors, some specifications have been changed. This has resulted in the replacement of four specifications with specifications one and six marked with an asterisk in Table 5 below.

Table 5. Updated Engineering Specifications Table. Specifications that have seen changes are marked with an asterisk(*)

Spec.#	Specification Description	Requirement or Target (units)	Tolerance	Risk*	Compliance**
1*	Velocity efficiency	90%	Min	H	I
2	Sampling Rate	200 Hz	Min.	M	I
3	Data Resolution (3DOF Linear Motion)	1 mm	Max	L	A
4	Cost	$1000	Max	M	A
5	Absolute Tip Deflection	0.01 mm	Max	M	A
6*	Data Streaming Latency	100 ms	Max	L	T
7	Assembly Time	20 minutes	Max	L	T
8	Allowable Leg Mass	1.25 kg	Min	M	A
9*	Operating Leg Speed	1.3 m/s	Max	L	A

Reasoning behind changes regarding specifications 1 and 6 are discussed in 5.2 Planarizer Dynamics and 5.7 Data Acquisition System and Analysis. Additionally, after some discussion with our sponsors, we have concluded that 1.3 m/s is a more reasonable operating speed for the robot leg, so our team will design for that speed instead. Additionally, the sponsor removed the requirement to design a 'catch mechanism' that would protect the robotic leg from fall damage should anything go wrong during its testing.

5.2 *Planarizer Dynamics*

The greatest concern we had when designing the planarizer was on how to minimize the dynamic effects that the planarizer had. The dynamic effects need to be limited so that the robot can hop with a steady state gait in a manner that is similar to if the planarizer was not there to support it (i.e real quadruped like conditions). Analysis on the planarizer dynamics has been done with respect to inertial load and vibrational effects. Damping and potential energy storage has been neglected in our evaluation of the system due to time constraints. Additionally, to alleviate any damping effects and frictional losses that the system may have, we have opted to use ball bearings where we deem appropriate.

Analysis of the inertial load was done using an energy analysis. The specific analysis is available in Appendix M: Velocity Efficiency. The resulting equation is shown below :

$$\eta_{vel} = \frac{v}{v_r} = \sqrt{\frac{m_r}{\frac{\bar{I}_b}{l_r^2} + \frac{m_b l_b^2}{4 l_r^2} + \frac{\bar{I}_r}{l_r^2} + m_r}}$$

It compares the amount of kinetic energy attributed to the leg's linear velocity to the amount that gets sunk into the other forms of kinetic energy, such as the rotational motion of the robot leg and the motion of the planarizer. The final parameter achieved from this is what we have dubbed the velocity efficiency. Seeing as we neglected damping and assumed the system to be perfectly rigid, the velocity efficiency only depends on the effective masses in the system. Minimizing the contributions to the effective mass maximizes velocity efficiency. Additionally, reducing the angular speed that the system sees for any given linear velocity also helps keep more of the energy in the leg's linear velocity. Thus, it seems that the velocity efficiency is a parameter that accounts for the first three specifications in Table 4: apparent mass increase, apparent mass moment of inertia increase, and yaw path deviation. After discussing this with Dr. Xing, we have determined that using velocity efficiency to guide our design as opposed to those three specification targets would be best. However, we will not be guided solely based off this parameter. As such, the engineering specifications table has been updated to as follows:

The velocity efficiency was determined by finding the mass moment of inertia about the yaw and pitch orientations. This is outlined in 7.1 Velocity Efficiency Verification Test.

Concerns over how much the leg's orientation may change in a given time span based off of how fast it is moving were brought up in the same meeting where we discussed velocity efficiency with Dr. Xing. In response, we have now been given the requirement that the boom must be between 1.2 and 1.3 m (or 3.9 to 4.3 ft.

The vibrational analysis can be found in Appendix O: Vibrational Analysis. The calculations use Rayleigh's method to find the fundamental frequency of the boom. These calculations were motivated by concern over driving the planarizer close to or at its natural frequency. To avoid this issue, we wanted to ensure that the natural frequency of the planarizer stay above the provided design value of 10 Hz. Though the frequency is low, a good planarizer makes use of a long boom to better approximate the sagittal plane. This reduces the boom's stiffness in response to transverse loads, lowering the natural frequency. Using conservative inputs, one of them being a boom length of 6 ft, for the formulations determined in Appendix O, the natural frequency came out to 1000 Hz. Despite Rayleigh's method providing an upper bounding value, we believe that so long as we do not significantly change the boom from a 0.5 in outer diameter carbon tube and stay within the range that Dr. Xing asks us to for boom length, we would likely be safe in terms of the natural frequency.

5.3 Base Design and Analysis

The purpose of our base is to support the gimbal and keep our other subsystems upright. The base design has changed considerably since CDR. Initially, the base was to be manifested as shown in Figure 33 and Figure 34. After discussions with Cal Poly mechanical engineering faculty member Dr. Joseph Mello, we determined that this design would not be able to handle the bending moment loads as the leg would contact the ground. The area of concern was the base post screw, which had potential to shear off. His suggestion was implementing a design as shown in Figure 35. This design implemented a flange bearing and three leveling mounts. Flange bearings are rated to accommodate higher moment loads than the previous ball bearings we were considering. They accommodate these loads radially. Additionally, there are three leveling mounts which screw into the base plate. They act as columns and bear some of the loading due to the hopping leg as well. The encoder mounted onto the top of the base plate, and the slip ring would be mounted on the bottom side of the base plate. The base adapter, colored purple, would be to adapt from the rotating shaft to the clevis yoke. Going into manufacturing, this was our design of choice. However, while manufacturing this iteration, we encountered several problems. One was that it was difficult to machine within our tolerances on the manual lathe. We found ourselves having to scrap certain parts such as the base shaft and base adapter due to accidentally removing too much material. This came sometimes from lack of concentricity of the manual lathes themselves, as well as our limited skill on the machines. Additionally, we had difficulty drilling the encoder mounting holes into our steel base plate. The size of the encoder mounting holes was for a #4-40 screw (.089 pilot hole diameter). We ended up breaking several high speed drill bits, and even a carbine bit while attempting to drill this hole in 1" steel. After breaking the carbide bit, we determined to go forward with the alternative design as our final design in Figure 36.

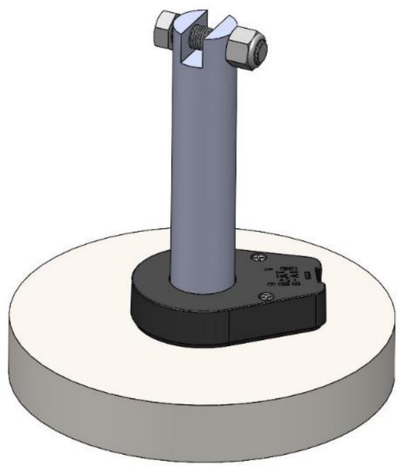


Figure 33: Initial Base Design

Figure 34: Base post screw and bearings

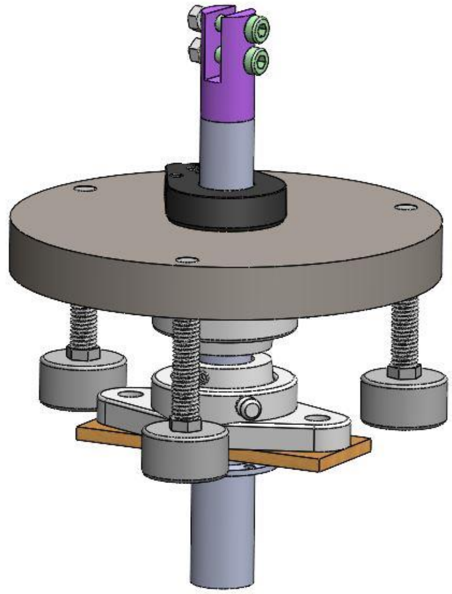


Figure 35: Base design with flange bearings and leveling mounts

This design utilizes a rotating shaft with two different diameters to mount bearings and the base encoder onto. A fixed housing is placed around that and screws into the base flange plate. The base flange plate is bolted onto a plywood sheet. The fixed housing is useful for preventing damage to the electronics due to humidity, dust, or impacts. The base adapter is epoxied into the hole of the base shaft. A cover plate is placed onto the housing to prevent additional dust from entering. Two radial ball bearings are spaced out and press fit inside of the housing onto the seats within the housing. These are shown in Figure 38. The 1" portion of the base shaft is what the bearings inner race is guided onto. This secure rigidity with the fixed housing and shaft adds additional stiffness the overall base assembly, and significantly reduces the failure mechanisms that the base post screw and flange bearing designs induced. The slip ring is placed onto the 1" portion of the shaft and is secured with a set screw into the top of the encoder plate. Wires feed out of the rotor side of the slip ring and out of the hole of the base shaft to go out to connect to the leg actuator wires. Wires feed out of the stator side of the slip ring to connect to the power supply. This is shown in Figure 37. The encoder is mounted onto the bottom of the encoder plate and sticks out of the front of the housing. With exception to the epoxying of the base adapter, this assembly was conveniently CNC machined and assembled by a family friend. The base shaft and fixed housing were turned on the CNC lathe. The cover plate and encoder plate were machined on the CNC mill. We extend our sincere gratitude to M&M Machining in Sloughhouse, CA for providing their services towards fabricating and assembling our base assembly.

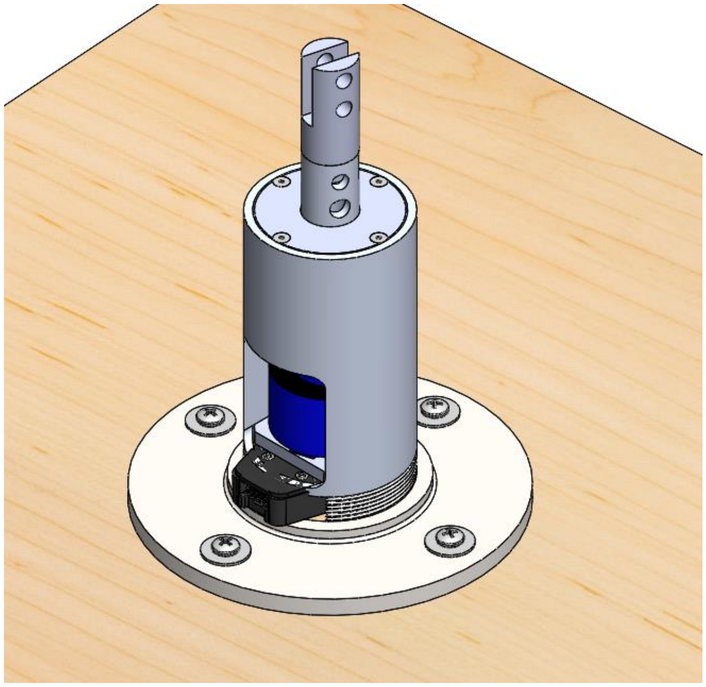


Figure 36: Base assembly isometric

Figure 37: Base assembly with slip ring wires

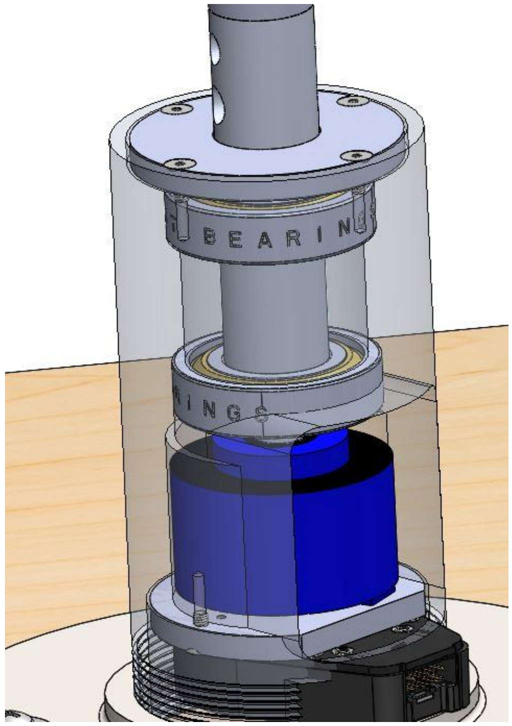


Figure 38: Ball Bearings configuration

5.4 Gimbal Design and Analysis

Per our sponsor's specifications, a system is needed to limit the robot leg to two degrees of freedom. To allow for the robots forward and upwards movement, we must allow the boom to rotate about the Z axis and X axis, based off of the coordinate system in Figure 15. To implement this, we have opted to move towards a design similar to Figure 15c. It is the simplest design that still accommodates our needs.

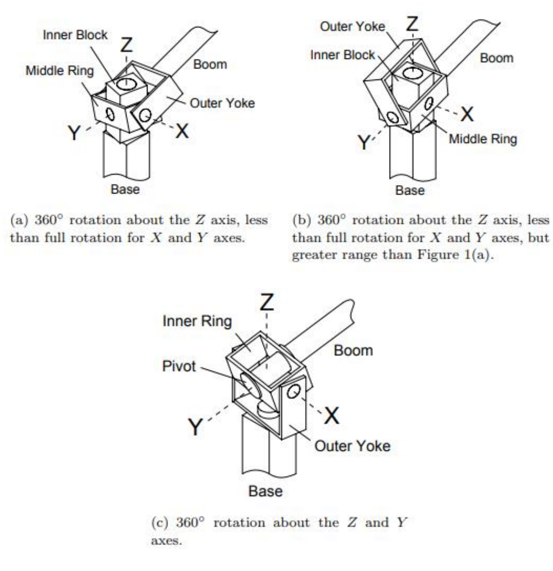


Figure 15. Referenced for 2DOF design

The two main differences between the gimbal we designed and the one show in Figure 15c are that our design does not allow for rotation about the Y-axis and that ours has been designed with the intention of using two booms instead. We will discuss the motivation for the two-boom implementation in 5.4 Boom Design and Analysis.

The gimbal assembly we chose is shown below in Figure 39.

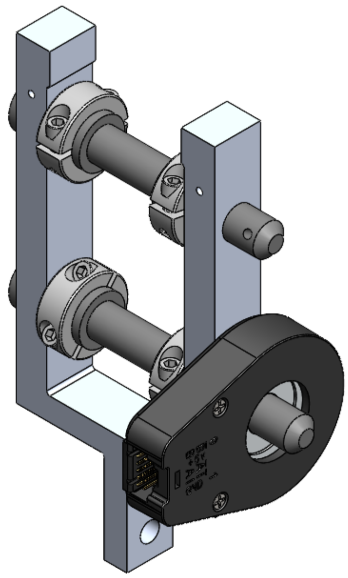


Figure 39. Gimbal assembly

We utilize a rectangular yoke with a tab on the end. The yoke that we are moving forward with is a custom-made yoke out of rectangular aluminum stock that has a width of ¾" in and overall height of 6 in. This height allows for the placement of two clevis pins, onto which the booms are attached. The tab at the end is ¾" tall. This tab fits into the slot on the top of the base adapter and is held in place by a 1/2" nut and bolt. This yoke rotates with the base adapter, as it rotates with the bearing. The pitch of the robot leg is controlled by two booms which are attached onto clevis pins. These ½" clevis pins are inserted inside holes drilled along the side of the yoke. The pins are spaced far enough so that there is not interference between the two booms as they rotate together. There are shaft collars placed on the clevis pins in order to limit translation of the booms along the shaft ends. Although with the shaft adapters we could limit the translational movement in the boom, we had no easy way of centering them in the first place. This led us to implementing ring shims on each side of the boom shaft ends, which would act as spacers to help limit the translation movement as well as keeping the booms centered along the gimbal.

Additionally, the gimbal must be designed to allow for proper encoder mounting and readings. An encoder is mounted on the outside of our clevis yoke around the bottom pin to track the pitch of the boom, which in turn will allow us to know the vertical position of the robotic leg. The encoder will be mounted by included mounting screws around the bottom pin on the outside of the gimbal. The cotter pin in our design would interfere with the encoder, which is why we decided to move forward without it. Its purpose was originally to prevent the clevis pin from moving and possibly falling out of the yoke, but this problem was solved with the addition of a set screw to fix the shaft ends to each clevis pin.

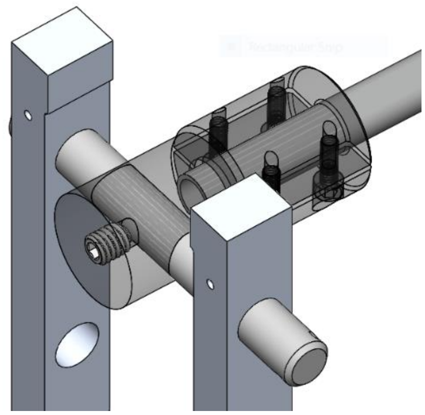


Figure 40: Transparent view of set screw from boom shaft end mounting onto top clevis pin Figure 40

By fixing the shaft end to the clevis pin using a set screw, the rotation of the boom will directly translate to the clevis pin which can be tracked by the encoder and the clevis pin will be fixed in every other direction. This set screw design is shown in Figure 40.

Another change made to our gimbal design since CDR was removing the top section of the yoke to make it Y-shaped. The reason for this design change was because we were worried the top of the yoke would interfere with the shaft end as it rotates up as the robotic leg jumps.

Finally, the last change to the gimbal design was adding threaded mounting holes to accommodate for the DAQ mount.

5.5 Boom Design and Analysis

As the largest possible contributor to the planarizer's function, the boom also has the greatest effect on the leg's dynamics. Accordingly, the boom's design is heavily guided by what was discussed in 5.2 Planarizer Dynamics. A long boom is fitting for sagittal plane approximation but also provides a large inertial load to the leg and suffers from a lower natural frequency. This is why we have opted to use carbon fiber for our boom. The high stiffness to weight ratio allows us to get the lowest inertial load increase and greatest natural frequency increase when compared to other materials. After some analysis using carbon fiber for the boom material, we discovered that resonance is not an issue, at least for the range of boom lengths that Dr. Xing provided us. We are then left to try and strike a balance between sagittal plane approximation and limiting the inertial load. We determined that this can best be done by maximizing the velocity efficiency. Based off of approximate numbers used before CAD, the velocity efficiency peaks closer to two feet, as shown in Figure 41.

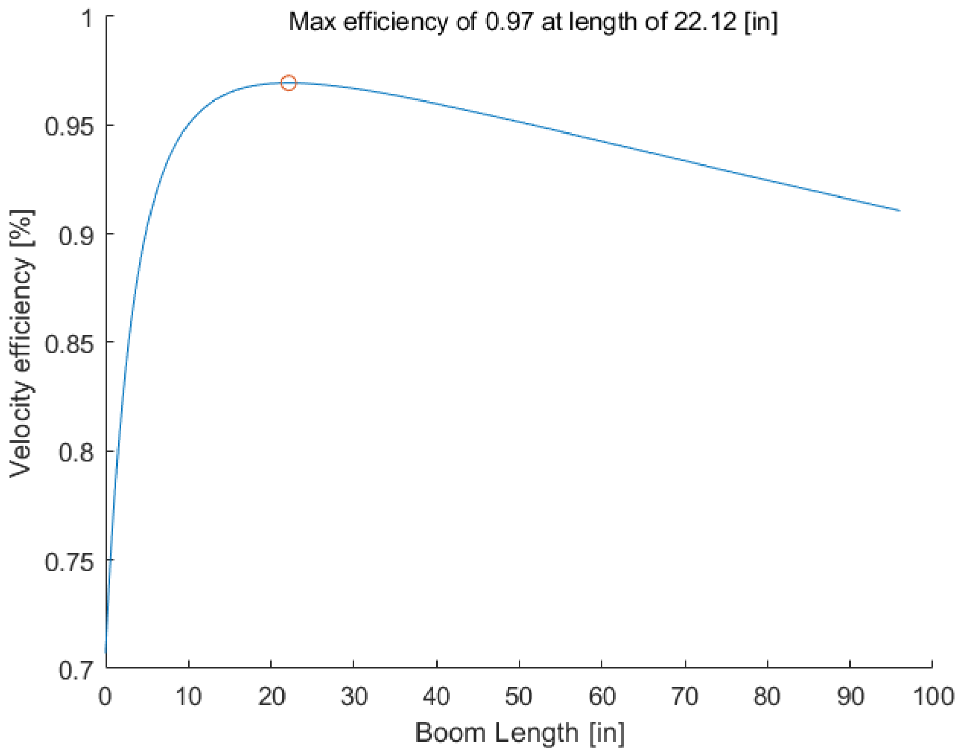


Figure 41. MATLAB plot of velocity efficiency for a double boom assembly using carbon booms of ID = 0.5 in and OD =0.56 in from Dragon Plate

Given the range of 3.9ft to 4.3ft, we have opted to go for the 4 ft option, based on this data. There is only a minor difference between 3.9 ft and 4 ft according to the figure above, but the manufacturer we used, Dragon Plate, readily sells carbon fiber at a 4 ft length. Concerns over handling carbon fiber properly to protect it from catastrophic failure has left us hesitant to make modifications to the product. We did not believe that the minor velocity efficiency increase is worth risking, so we proceeded with a 4 ft boom.

Calculations from Figure 42 suggest that the boom length should be increased to 4.3 ft, but since the manufacturer had it readily available at 4 ft, we decided to go forward with this length.

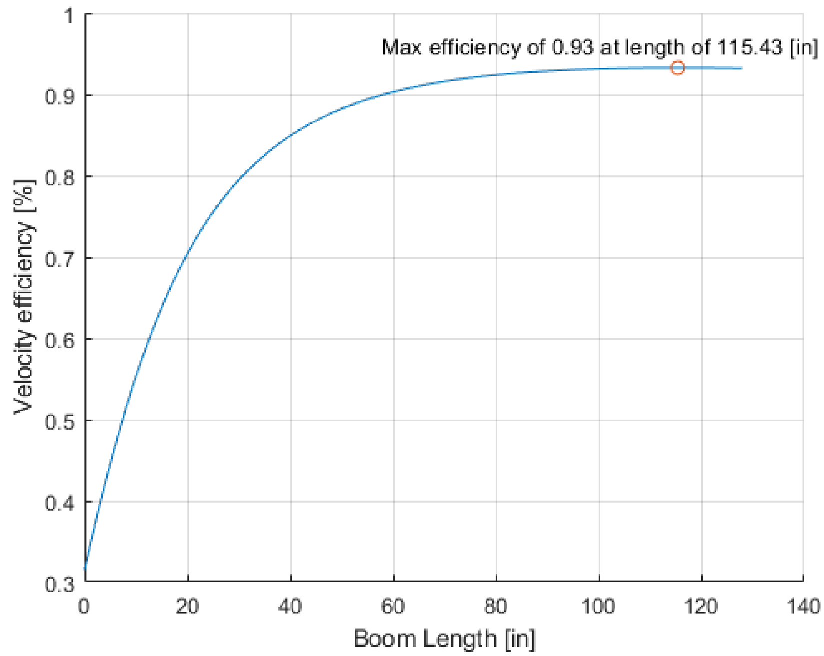


Figure 42. MATLAB plot of velocity efficiency for a double boom assembly using carbon booms of ID = 0.4 in and OD =0.5 in from Dragon Plate and more accurate inertial values derived from CAD

One additional function we wanted the booms to have was to restrict the pitch and roll of the leg. To do this, we leveraged the properties of a parallelogram. If we have two booms that we can ensure are always parallel, then so long as we can ensure that the mounting points are vertical on one side, the mounting points on the other side will necessarily also be vertical. Then, by using two booms, we can ensure that the mount from the boom to the robot, and therefore the robot, is always vertical. Additionally, having it so that we have two points of contact will allow the planarizer to better react against pitching moments. This should not only support the sagittal plane approximation, but also help us comply to the 2DOF model that we are trying to test for.

The booms are connected to tube connectors so that the mounting bolts are not going directly into the booms. This way, there are not holes in the booms that could create stress concentrations that would cause the boom to fracture. These carbon fiber tube connectors were bought off of the same manufacturer of our booms and are designed to clamp onto ½" OD shafts. They have 10-24 set screws through the side of these connectors to constrain to the booms.

5.6 Leg Mount Design and Analysis

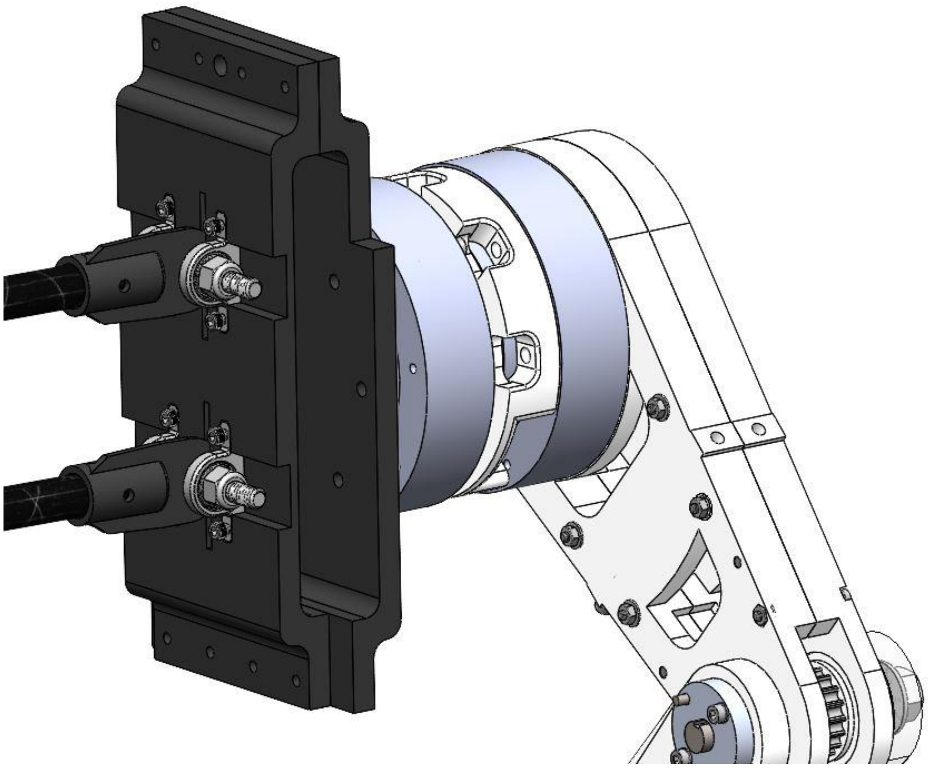


Figure 43. Leg mount, shown connected to booms on left and robot leg on the right

The leg mount consists of two tube connectors, two ¼-20 bolts, two low profile pillow block bearings, one adapter plate, and one mounting plate. Spacers are placed on either end of the tube connector in order to constrain the connector axially along the ¼-20 bolt to limit unnecessary movement.

Three goals that drove mount design were minimizing the total mass, minimizing friction in the mount, and supporting the 2DOF approximation that we were tasked to implement. Motivation for the first two goals were to reduce the impact that the planarizer has on the leg's dynamics. This places much higher emphasis on the first goal: minimizing total mass. Based off of the results of the analysis in Appendix M: Velocity Efficiency(higher velocity efficiency is better), mass distributed furthest from the post of the planarizer has the greatest impact on the dynamics, as it increases the moment of inertia of the system about the post. Friction is also a concern. While no analysis has been done here, based off of our intuition, we believe that bearings are necessary, especially this close to the robot leg. Bearings further down the boom have a much larger lever arm acting on them, so resistance seen in those bearings are much less significant to the robot leg. Both the mass and friction issues steered us towards this design iteration.

One design previously considered used rod ends. The design intention behind rod ends was to account for any misalignment due to manufacturing tolerances and their potential effects on how the planarizer attempts to restrict pitch in the robot. However, rod ends are unideal in terms of both weight and friction. They are inconveniently large and heavy, and while they do make use of bearings in them as well, they tend to experience a not insignificant amount of stiction. To our good fortune, concern over misalignment was alleviated when we made our structural prototype. Despite being strewn together with just good enough parts and being manufactured without precision in mind, there did not seem to be any issues with binding in the mechanism or pitch restriction. As such, we were able to confidently stray away from rod ends, moving towards the design in Figure 43 shown above.

In regard to sturdiness, we are fairly confident that the mount designed can take the loads we expect. We have avoided making a totally fixed connection between the booms and the robot, at least where it counts in terms of stress. Additionally, the loads we expect to see are at a peak of only 27lbs. This allows us to continue with using plastic for the backplate. The bearings selected are rated to see at least 27 lbs, though based off of the load conditions, each should see at most 15 lbs. The greatest concern in terms of loading is that it is periodic. To handle the vibrational loading, the bolts used to mount the pillow block bearings to the adapter plate will be secured using spacers and lock nuts.

5.7 Data Acquisition System and Analysis

To reiterate, the goal from our DAQ was initially to have at least a sampling rate of 200 Hz, hold a resolution of 1mm or better, and hold an upload time of 15s. However, after some discussion with Dr. Xing, we streamed the data to a computer as opposed to collecting and then bulk uploading data. The main hardware for this will consist of two STM32L476RG Nucleo64s, two HiLetgo HC-05 Bluetooth modules, and two ½" bore encoders from US digital, both of the same model: E6-10000-500-IE-D-H-D-3. The microcontroller's 80MHz core should be more than capable of handling our data collection needs both in terms of meeting our sampling rate and reducing the latency between data collection and it being plotted live in MATLAB. The results of our DAQ test are outlined in Section 7.2 DAQ Test.

Although the E6 encoders from US Digital were recommended to us by the sponsors, we needed to choose configurations that would fit our needs. The primary configurations we had to consider were CPR (cycles per revolution), bore size, and either single or differential output. We configured the encoders with the highest available CPR, 10,000, while ensuring we avoid overflow error. The hand calculations for maximum CPR are available in Appendix N: Encoder Selection Calculations. For both of our encoders, we initially chose the differential output model, as we thought it would be helpful for filtering out common noise. We later found that this was unnecessary, and that the extra wired connections for a differential output would be cumbersome. We are now using them as single ended encoders.

We initially thought that the slip ring would eliminate our electrical connection issues. We were aware that the slip ring may induce noise into the encoder readings, but we felt that we could handle it by researching filtering methods. However, we had difficulty finding resources for this online and instead looked towards wireless transmission of the pitch data. This led to us using two HC-05 bluetooth modules and two STM32L476RG Nucleo64s.

The backend was coded in C++ using PlatformIO in VSCode. The frontend is in MATLAB. All data collected is live plotted in MATLAB, and exported after the test is finished. For more information about the DAQ, including the github link, electrical connections, and documentation, refer to Appendix W.

5.8 Safety, Maintenance, and Repair Considerations

As far as safety goes, there are only minimal concerns. We are dealing with electronic hardware, but our microcontroller only needs a 5-volt input at low amperage, so we are well below the 40-volt safety threshold. The area around the planarizer as it is being tested must also be cleared, with no obstructions within the area the leg moves around.

Concerning maintenance, the planarizer is very robust. The planarizer will only be tested a few times a year, up to the discretion of our sponsor, so fatigue is negligible compared to our concern over wiring. The mount will likely incur the most stress and is the area with the greatest chance of failure. That is why our gimbal design must be robust to handle the two degrees of freedom. The bearings should help with this by reducing wear and prolonging the lifespan of rotating components.

The lifespan of our planarizer is determined by a fatigue analysis based on the frequency of how often it is being tested, but we expect our planarizer to last for at least 10 years. Parts wear out, so the sponsor should ensure the structural rigidity of our connection points. Particularly, the fasteners are likely to fail before other components; these must be visually inspected. Fortunately, fasteners are easy to replace. We are expecting very low loads of 15 pounds, so the booms should be nowhere close to their endurance limit, and such are of very little concern.

5.9 Cost Analysis

The total budget for building and testing the planarizer is $1000. This entire budget is shown in Appendix S: Project Budget. The entirety of the costs of this project are expected to be for purchasing necessary materials, with no costs for outsourcing any manufacturing processes. Looking at the indented Bill of Materials (Appendix R: Indented Bill of Materials), the total cost of this project is estimated to be $757. The entire cost of the project, including shipping and spare parts, comes out to be $1111.40.

Looking at Table 6: Bill of Materials, which outlines the expected cost of each component of the planarizer, the largest purchases will be the two E6 encoders from US Digital and the machinable shaft ends from McMaster, with each of these purchases being around $200.

Table 6: Bill of Materials

Subassembly	Raw Material / Equipment	Quantity	Cost ($)
Base Assy	Base Plate White Oak Plywood	1	$ 18.22
	Base Flange	1	$ 16.00
	.266 ID, .875 OD Washers	4	$ 0.37
	1/4"-20 Thread, 1-1/8" Long Pan Head Phillips Screw	4	$ 11.19
	1/4-20" Hex Nut	8	$ 0.44
	Fixed Housing	1	$ 48.04
	Base Shaft	1	$ 13.21
	R16-ZZ Ball Bearings	2	$ 12.30
	Retaining Ring	1	$ 0.23
	Encoder Plate	1	$ 9.79
	Encoder Plate and Cover Plate Screws	8	$ 0.61
	Cover Plate	1	$ -
	Base Adapter	1	$ -
	5/16" Shoulder Bolts	2	$ 8.12
	1/2" Bore Slip Ring	1	$ 35.94
	1/2" Bore Encoder	1	$ 127.84
Gimbal Assembly	Clevis Yoke	1	$ 38.70
	Carbon Steel Ring Shims	4	$ 2.52
	Clevis Pins	2	$ 5.09
	0.5" Pin Locking Shaft Collars	4	$ 19.64
	1/2" Bore Encoder	1	$ 127.84
Boom Assembly	0.5" OD Boom	2	$ 59.80
	Boom Shaft Ends	2	$ 101.22
	Boom Set Screw	1	$ 0.28
Leg Mount Assembly	CAN Side Mount	1	$ -
	Main Leg Mount	1	$ -
	Left Spacer	1	$ -
	Right Spacer	1	$ -
	Lock Nuts	2	$ 0.11
	Carbon Fiber Tube Multi-Angle Connector	4	$ 13.00
	Mounted Shielded Steel Ball Bearing	4	$ 68.16
	1/4" Bolts	2	$ 0.22
	#5-40 Bolts	8	$ 0.05
	#5-40 Nuts	8	$ 0.63
DAQ Mount Assembly	DAQ Mount Plate	1	$ -
	DAQ Mount Bolts	5	$ 0.05
	DAQ Mount Nuts	5	$ 0.40
	Power Bank	1	$ 16.62
	STM32 L476RG Microcontroller	1	$ -
Total		**$757**	

5.10 Previous Concerns

One main concern of our design was the cable management. This includes the cables that will power the robotic leg as well as those that supply data and power to and from the encoders and the microcontroller. Due to our design and data acquisition system, different electrical components connected by cables will be rotating relative to each other, inevitably leading to cables being wound up. This is a concern because this limits the amount of time the robotic leg could be tested for. Seeing as the robot should be able to run for slightly longer than when it hits a steady state gait, the winding is fairly problematic. Another concern is that the electronics could be damaged from being pulled from the tightening cables.

We accounted for this concern by implementing a slip ring within our base design. Slip rings allow for the transmission of electrical signals from a stationary to a rotating structure. The implementation of slip rings should allow the robotic leg to be ran for as long as desired. The slip ring is attached to the base shaft, and the rotor wires feed through the base shaft and out to the leg. The stator wires feed to the power supply.

For future users of the planarizer, extending the length of the cables should be considered. Concerns of the robotic leg not being able to reach steady state due to testing duration could be eliminated. With both solutions, however, the user would still need to watch for and stop the robotic leg in case the cables become wound up.

6. Manufacturing

This section is a guide detailing all the manufacturing processes of our machined parts for our planarizer and how each component fits into each subassembly and ultimately our full assembly. We purchased most of our components, but our clevis yoke fitting, shaft adapter, base housing, and shaft ends had to be modified. As well, the boom sleeves must have holes drilled through for set screws to tighten the boom. These custom components will be manufactured at either Mustang 60 or the Hangar Machine Shops on campus. The corresponding drawings are available in Appendix U: Layout Drawings. Additionally, our leg mount, which acts as the interface between our boom and leg, was printed. Finally, our budget status can be found in Appendix S: Project Budget. In summary, we are about $100 over budget, having spent $1200 in material costs and returning about a $100 worth of parts that either got scrapped or the manufacturer erroneously sent.

6.1 Material Procurement

Most of our parts were sourced from vendors, notably McMaster-Carr. We acquired these parts from various online retailers and all lead times were less than two week. Refer to Appendix R: Indented Bill of Materials for a detailed list of which materials are procured. An instructional guide on manufacturing critical components is described below.

6.2 Clevis Yoke Fitting

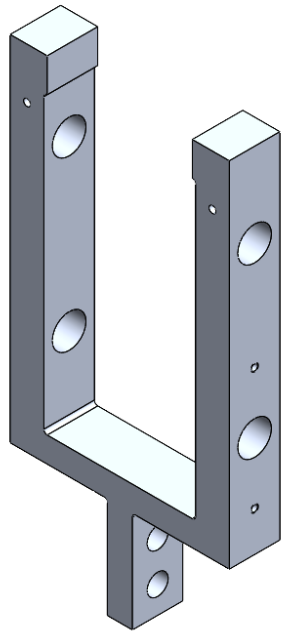


Figure 44. Clevis Yoke Fitting

The clevis yoke fitting is a crucial part in the gimbal assembly that fixes our boom sleeve in place while allowing for the boom to pitch up and down on the clevis pins while the yoke rotates about the base adapter. We water jetted rectangular aluminum stock to give us the full profile of the yoke. The manual mill was used to drill holes in their precise locations with the assistance of a digital read out.

Step 1: Acquire rectangular aluminum stock 6” x 3” x 1” (height x length x width)

Step 2: Waterjet yoke profile

Step 3: Use hand sander to deburr edges from waterjet

Step 4: Use manual mill to drill 0.375” hole through the tab 0.25” from the bottom of the yoke

Step 5: Use manual mill to drill 0.5" hole through the entire yoke, 2.25” from the bottom of the yoke

Step 6: Use manual mill to drill 0.5” hole 4.5” from the bottom of the yoke

Step 7: Use manual mill to drill 2 #4-40 holes on one side of yoke for encoder mounts, same axis as clevis holes

Step 8: Deburr holes with Dremel rotary sanding bit

6.3 Gimbal Boom Sleeves

To fix the boom to the gimbal we fit the boom into an aluminum sleeve which is pinned to the gimbal. This allows the boom to still pitch up and down. The boom is then fastened onto the boom sleeve while the clevis pin is fitted in the sleeve. The sleeves are carbon steel machinable shaft ends that will be purchased from McMaster-Carr. There will be two of these sleeves, one for each boom.

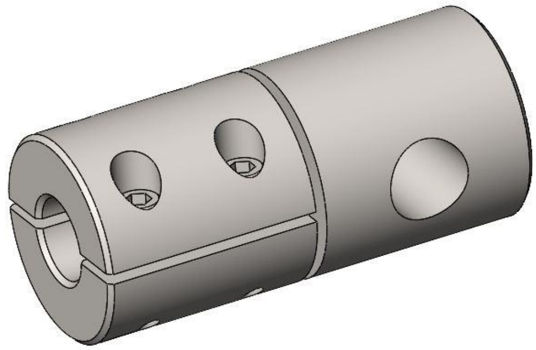


Figure 45. Boom shaft end sleeve attached to gimbal

Step 1: Scribe line across length of sleeve with chalk to ensure that the hole is in the middle of the sleeve with respect to its height

Step 2: Use manual mill to drill 0.5" hole 0.5" away from the end of the cylinder that does not have the hole on the face

Step 2: Deburr hole with Dremel rotary sanding bit

6.4 *Leg Mount Shaft End*

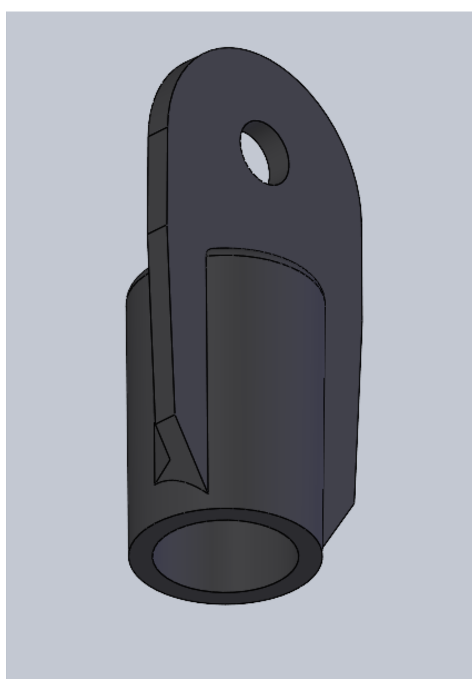


Figure 46. Boom shaft end sleeve attaching to clevis rod end for the leg mount

Step 1: Use drill press to drill 3/16” center of shaft end, positioning does not need to be exact

Step 2: Use tap to cut ¼”-20 internal threads

Step 3: Deburr edges with Dremel rotary sanding bit

6.5 Base Adapter

Securing our gimbal to our flange base is the base adapter. This piece is meant to rotate with the gimbal assembly; additionally, there is an encoder mounted to the bottom of this adapter to record the angular position as the planarizer yaws about the base.

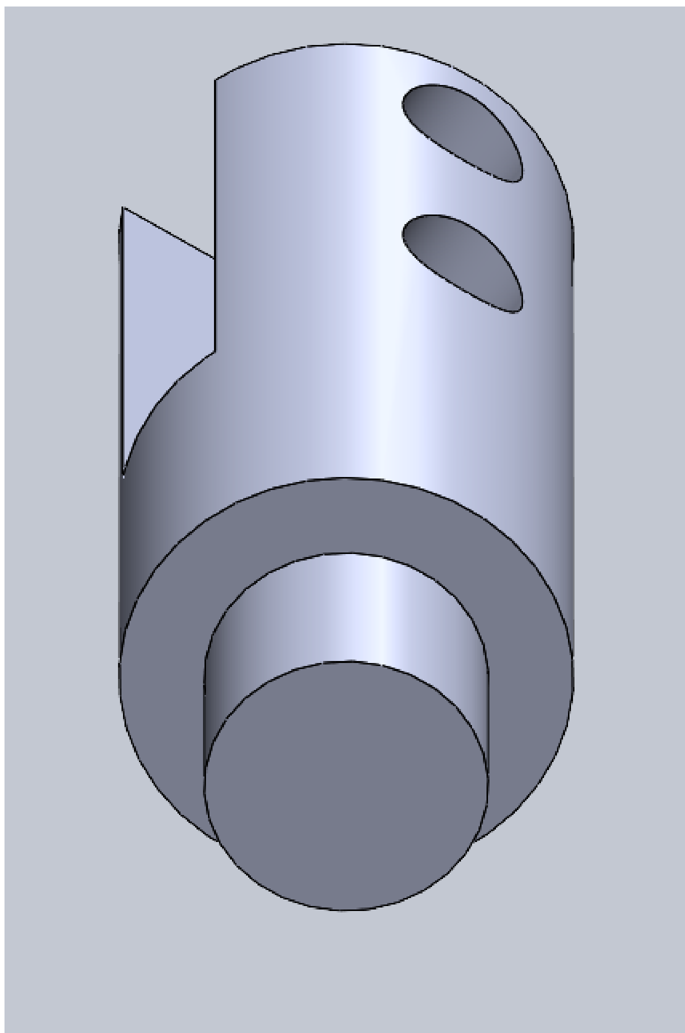


Figure 47. Base adapter with a view of the turned plunger

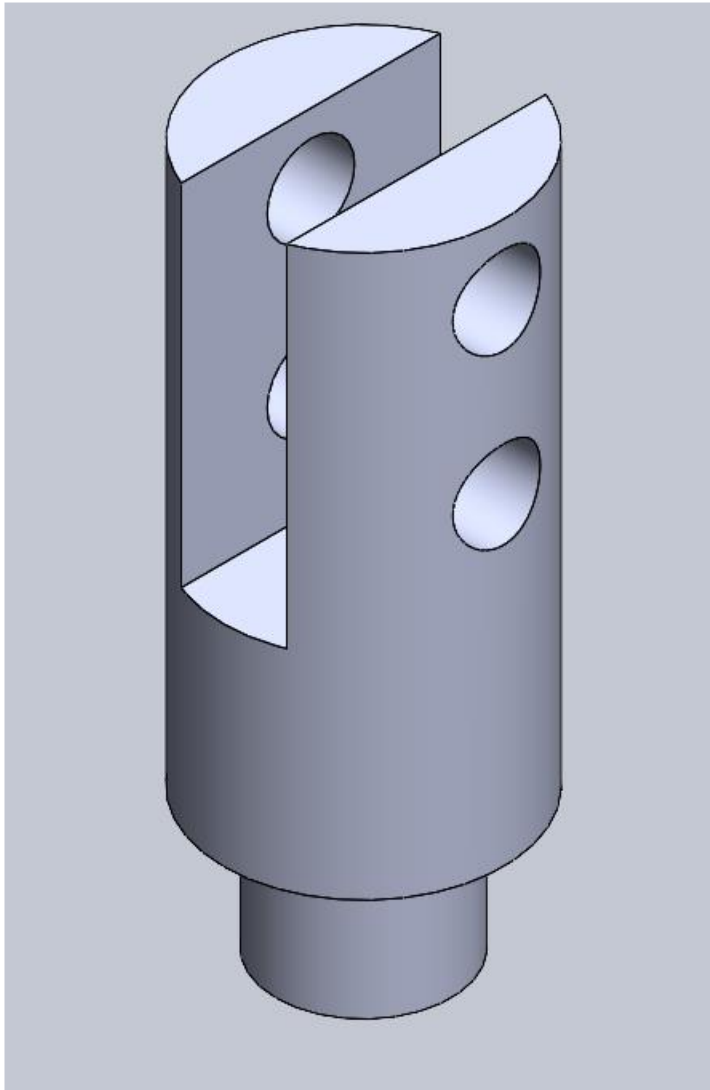


Figure 48. Base adapter isometric view

Step 1: Face stock to 2” length on manual lathe

Step 2: Turn the stock to an OD of 1”

Step 5: Mill rectangular keyway off the top of the cylinder using 3/8” end mill; End mill needs to be centered with the vertical axis of the part (0.5+0.375/2 from the edge), Slot is 1.25” deep

Step 6: Use manual mill to drill a 0.375” hole in the plane normal to the keyway just cut. Hole is 0.25” from the top of the adapter

Step 7: Insert end that has just been machined into the jaws of the manual lathe

Step 8: Insert drill chuck into tailstock and turn bottom 0.5” down to a diameter of 0.75”

Step 9: Use rotary Dremel bit to deburr holes, use file to deburr edges

6.6 *Base Housing*

The base post screw attaches the base plate to the base adapter. The top is press fit inside the adapter while the threads on the bottom will screw into the supporting base plate.

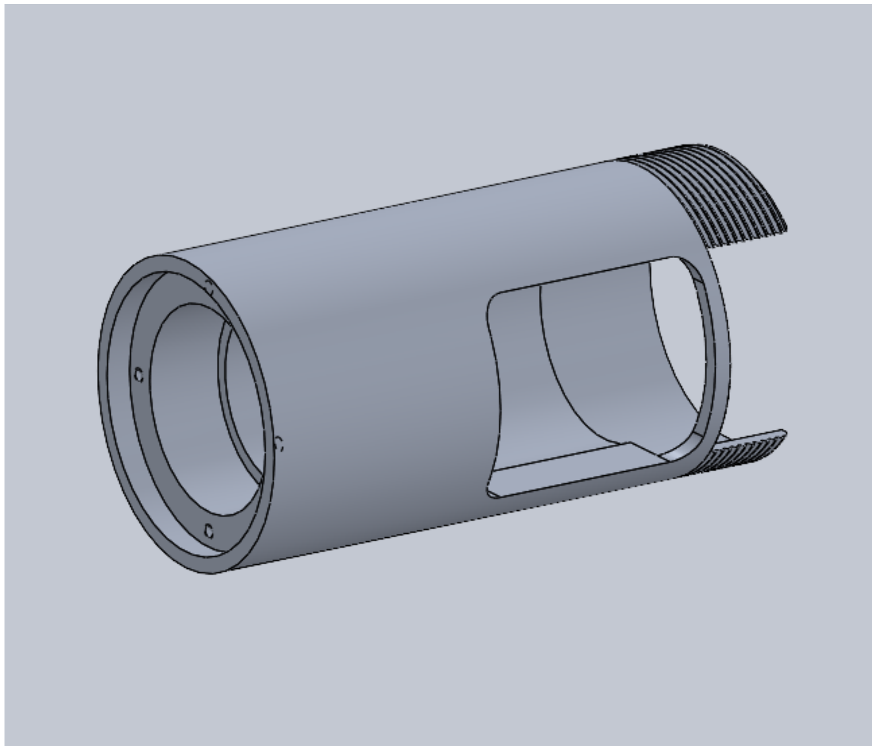


Figure 49. Base Housing

Step 1: Once the housing is done on the CNC, secure the housing upright in a vice.

Step 2: Mill off the thin aluminum section connecting the housing together with a 3/8” endmill. The entire section must be milled off until there is an unobstructed pocket at the bottom of the housing.

6.7 Base Plate

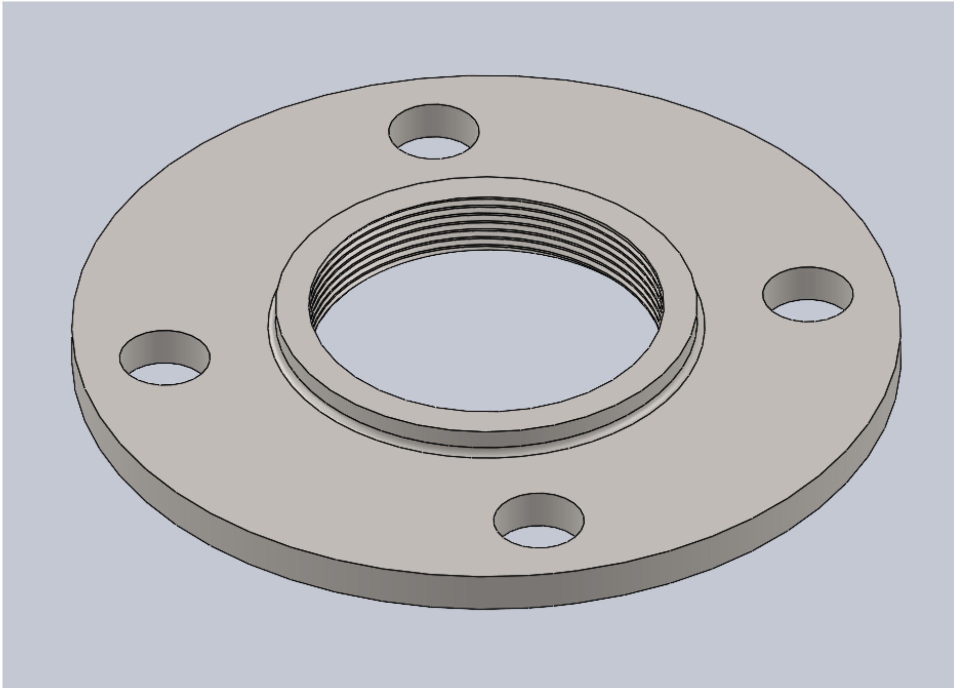


Figure 50. Top Isometric View of Base Plate

Step 1: Base plate will come with holes already CNC'd. Set the plate securely in a vice.

Step 2: Use a right-handed ½" die to thread the inside of the center larger hole.

6.8 Assembly

Once all the parts have been modified and/or purchased, assembly of our planarizer can begin. It is easier to work by subassembly, so we will build from the bottom up.

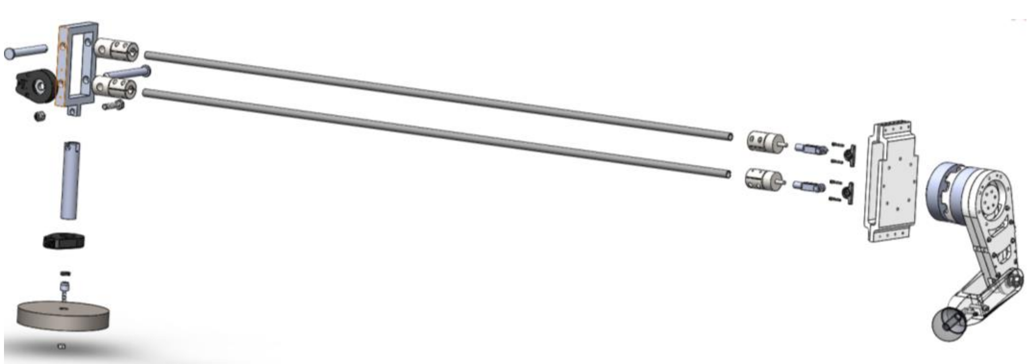


Figure 46: Exploded View of Entire Assembly

6.8.1 Base Assembly

The hardest components to mate together in our planarizer are the bearings within the base adapter. In Figure , the bearings can be seen press fit in between the base adapter and the base shaft. To achieve this mechanism, we must first press fit the bearings within the top of the base shaft by heating the bearing in an oven while simultaneously freezing the base shaft. When they are brought together after being temperature treated, the bearing is allowed to slip onto the base shaft. When the temperature of both materials reaches equilibrium, the bearing contracts back to its original shape and the base shaft expands back to its original shape. This insures a nice, snug fit for the bearing.

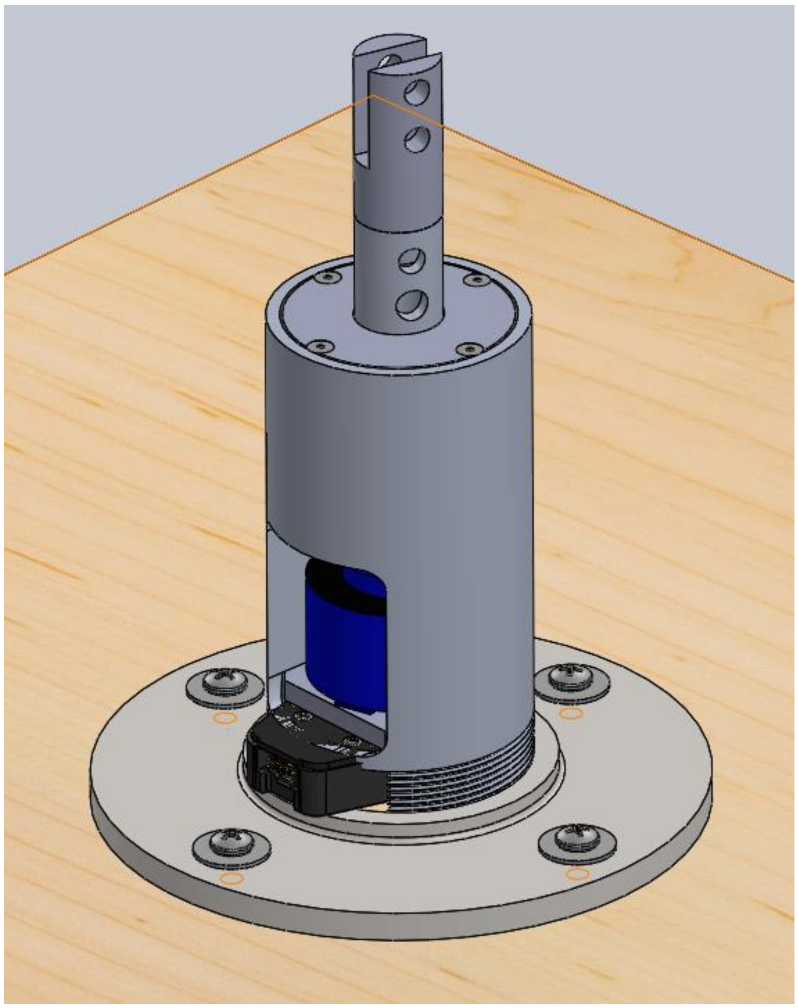


Figure 47: Base Assembly Isometric View

Next, we must press fit the bearing-shaft duo to the base adapter by epoxying the base adapter to the shaft. We then fit the bearings snugly inside the base adapter. Then, the encoder wraps around the base shaft as shown in Figure 47, where two #4-40 screws can securely lock the encoder in place atop the flange. Lastly, the base plate is rotated around the base housing to be screwed into place.

6.8.2 Gimbal Assembly

Connecting the yoke securely to our base adapter is two 3/8" – 24UNC bolts and nuts. To attach the boom, we must first fix the boom sleeve within the yoke with a clevis pin for each boom. These pins should fit snugly within the yoke. Refer to Figure 39 to see the full gimbal assembly with clevis pins inserted. Once the pins are inserted through the sleeves in the yoke, shaft collars will prevent the boom sleeves from translating. Additionally, a cotter pin is placed in a small hole at the end of each clevis pin to prevent the clevis pins from slipping out.

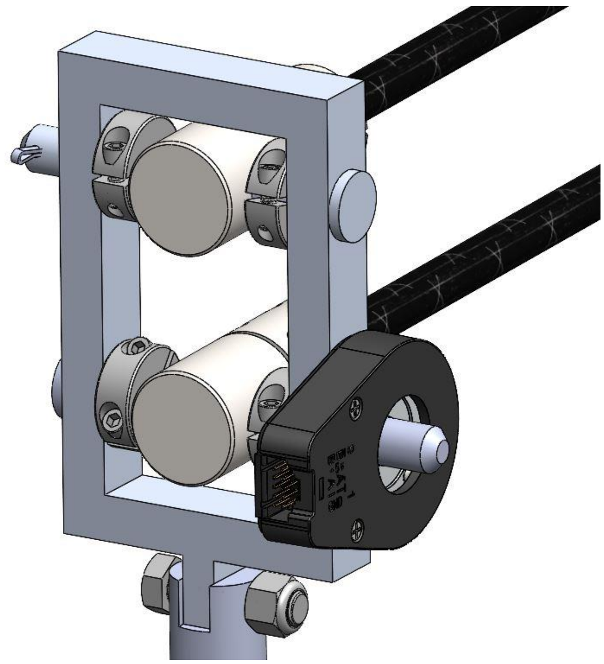


Figure 48. Full gimbal assembly with boom and sleeves fitted in.

6.8.3 Boom-Mount Assembly

These two will form the last subassembly as the boom is clamped down by machined shaft ends on either side. This will rigidly secure the boom so that it can only rotate with the mount-yoke assembly. The booms are shown fitted into the sleeves in Figure 49. On the mounting side of the boom, clevis rod ends are fitted inside pillow block ball bearings. These bearings are bolted into the mount. The mount assembly is found in Figure 50.

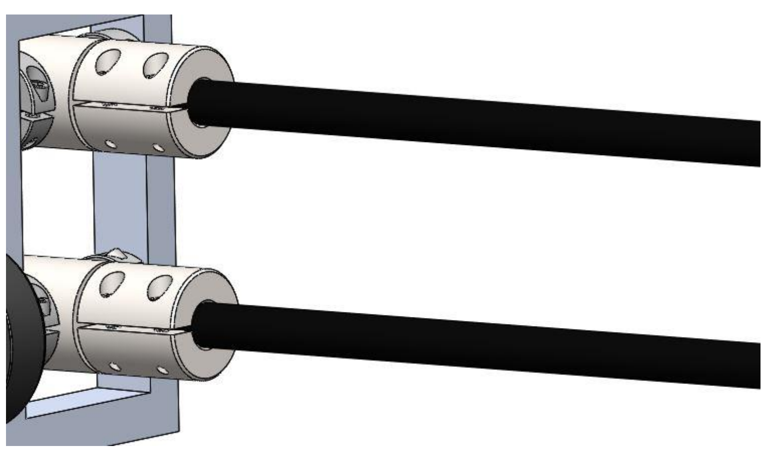
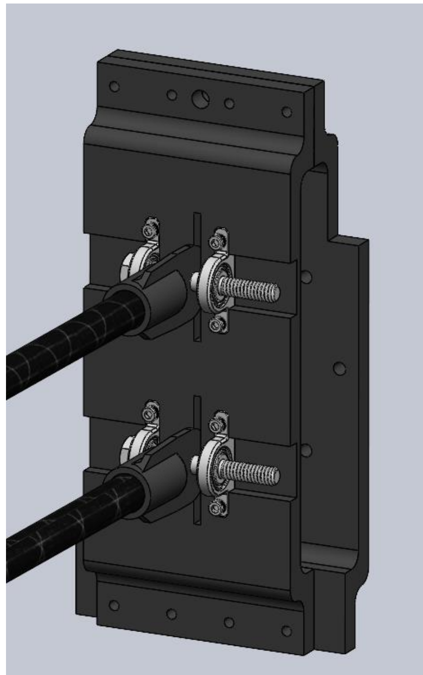


Figure 49: Boom fittings within sleeves

The other side of this subassembly sits the leg mount-boom interface shown below.



Error! Reference source not found.

7. Design Verification

See Appendix Q: Design Verification Plan for the complete design verification plan. Refer to Table 5 for more information on the specifications to be tested. Note that specifications 4 and 9 were not going to be tested. Dr. Xing considered the operating leg speed (Spec 9) when he provided us with a range of possible boom lengths. Accordingly, any boom length that falls within that range satisfies the specifications. Cost (Spec 4) is not a specification to be verified in testing. All tests were performed in ME Labs, where the current robot leg is readily available for use. We finished assembling our prototype at the end of winter quarter along with all our tests.

7.1 Velocity Efficiency Verification Test

The primary purpose of the first test was to verify the predicted velocity efficiency value. The velocity efficiency serves to encapsulate and perform the balancing of specifications 1, 2, and 10, so instead of reaching for arbitrarily set requirements for the three, we have opted to use the velocity efficiency to optimize our design. To do this, we must find the moment of inertia of the assembly and weigh the individual components. The technique for determining the moment of inertia and approximate the center of gravity was taught in our Mechanical Vibrations class, so the corresponding lab has the necessary equipment to perform our test. As well, Home Depot provided us with the necessary materials to quickly build a test stand for it. To do so we simply swing the rotating portion of the assembly as a pendulum. By measuring the period of its oscillation and comparing it to the distance to the center of mass, the center of mass can be found easily by simply hanging the assembly strategically at multiple points. Masses are easily obtained by weighing them on scales. After getting all three, we have determined the velocity efficiency. This sets us up for future tests, for if we want to see the effect of the velocity efficiency more accurately on criteria like the torque that the robot needs to operate and how that affects the steady state hopping of our planarizer.

A very thorough analysis of our testing results can be found in Appendix X: Velocity Efficiency Verification Test. In summary, using our own metric of velocity efficiency we did not meet the sponsor's specification of 90%. Our overall velocity efficiency was 78%, 13.3% short of our goal. There are a couple reasons for why we have not met our specification, notably the fault in our testing. We had two times farther apart for the yaw inertia test than the pitch inertia test. We tested both orientations to their maximum oscillations, but the yaw inertia test had more variability. If we ran more tests, we're confident we would have a period that correlated more with the true natural frequency. As well, there is a heavy amount of damping that we did not account for and were unable to compute. We simply assumed negligible damping to simplify our calculations. Assessing the performance of our design, our prototype is adequate because of this test. We have not hit our goal, but we have come close, and perhaps a reduction in damping would lead to a larger natural frequency thereby increasing our velocity efficiency according to our calculations in Appendix J: Yaw Motion Dynamic Analysis. We have learned a valuable lesson in that our models in our calculations may not truly represent the system we envision it to, and that experimentation may sometimes lead results rather than simulate them.

7.2 DAQ Test

This purpose of this test is to verify the functionality of the DAQ, improve the data quality of the DAQ, and evaluate the user friendliness. We also wanted to make sure that all of the wiring is robust and that it will function when testing occurs. We felt that we have met all of these, though we also found that we were unable to meet all of the customer specifications. During this test, we looked at Bluetooth latency, quality of the streaming feature, and the polling rate. We measured the Bluetooth latency to better correct for it in our code, improving our data resolution. This came out to an estimated latency of 6.9ms. To correct for this, we have the microcontroller responsible for Yaw wait 6.9ms before zeroing its time. We also wanted to adjust the streaming latency to ensure a good user experience. We had a target of 100ms, and we were able to measure a streaming latency of 90ms. There was no issue with this. We were unable to hit a polling rate of 200Hz. Due to time constraints, we were only able to hit 60Hz, which also meant that at the predicted max speed of 1.3 m/s, that the lowest uncertainty we could have is 6.5mm. There were issues with being able to send data fast enough with little corruptions over Bluetooth, resulting in the 60Hz. The details of this test are available in Appendix Z: DAQ Test.

7.3 Three Point Bend Test

Appendices/Resources: Test Procedure, Uncertainty Prop for E, Data Resolution

The goal of this test was to statically load the carbon fiber boom and measure the deflection. Based on this deflection, the Young's modulus was obtained and compared to the manufacturer specification provided by DragonPlate. The boom was placed on rollers, with each on its own table as shown in Figure 51. Dumbbells of varying weights were suspended by a rope from the center of the boom. A height gauge was placed at the center of the boom to measure the deflection from its unstretched position. We expected a maximum load of 27 lb due to the ground reaction force of the leg. To be conservative, we tested our boom under a load of 35 lb. The deflection values from these tests seemed to be significantly larger than our expected maximum deflection of 1 mm for a 15 lb load (12.3 mm deflection in reality). It was useful to conduct this test to verify that the carbon fiber does not fracture under load, but it was disappointing to realize that the provided booms were not as stiff as we thought.

Figure 51: Three Point Bend Test setup

Table 7: Three Point Bend Test Deflection Results

Trial	Height Gauge Reading	Approximate Weight	Deflection (y_a)	Measured Weight	E Uncertainty %
1	1.5375	Unloaded	0		
2	1.052	15 lb	0.4855	16.06	26.63
3	0.929	20 lb	0.6085	20	21.32
4	0.490	35 lb	1.0475	36.06	12.56

Based on the deflection value for a 15 lb load, we determined the true stiffness of our boom by calculating Young's Modulus. The reference parameters for computing this are in Figure 52. The corresponding equation is below as well.

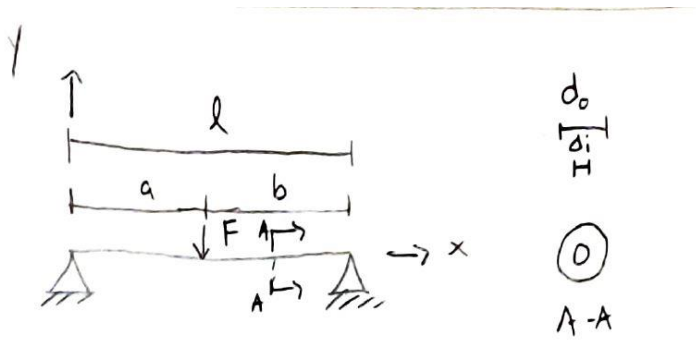


Figure 52: Reference figure for computing Young's modulus

$$E = \frac{32(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a l({d_o}^4 - {d_i}^4)}$$

We computed Young's Modulus to be 1.87x10^7 psi. The DragonPlate rating for this was 3.30x10^7 psi. Our boom was proven to be much less stiffer than expected. The uncertainty within the Young's Modulus was computed as well. This was based on root sum squaring the uncertainty contributions of all of the parameters as shown in Figure 52. These contributions are shown in Table 8. The calculations for these uncertainty contributions are shown in the Analysis section of Appendix Y: Deflection Test.

Table 8: Uncertainty Analysis Table

Measurement	Theoretically Measured Value	Uncertainty	dE/d	Contribution
F	16.06	1	1.11E+06	1.22E+12
a	18	0.25	3.06E-10	5.87E-21
l	36	0.125	-3.94E+06	2.43E+11
ya	-0.4855	0.125	-3.66E+07	2.09E+13
do	0.5	0.0005	8.88E+06	1.97E+07
di	0.4	0.0005	4.54E+06	5.16E+06
b	18	0.05	3.06E-10	2.35E-22

The uncertainty calculated was 4.73x10^6 psi. On first inspection, this seems like a high value, but the high uncertainty contributions of the force and deflection drive this uncertainty up.

More thorough details of the Three Point Bend test are available in Appendix Y: Deflection Test.

7.4 Assembly Convenience Test

This final test acts to ensure that our assembly can be reasonably assembled. This is less of a performance factor and more of a convenience factor. If our team can reasonably assemble the planarizer and hook it up to the robot leg in a short time, then we would feel comfortable in saying that it will not significantly impact the testing schedule for the Cal Poly Legged Robots Team. Our original estimate of an assembly time of 20 minutes was made before any manufacturing took place. To conduct this test, the entire planarizer was completely disassembled with the exception of the base enclosure, which includes bearings that are press fit onto the center shaft. We do not expect this base enclosure to be disassembled for storage or any other possible reason, so its assembly time was not included in our test. The total final assembly time for our Planarizer resulted in a time of 39 minutes and 40 seconds. Due to there being 16 total 1/8" bolts and lock nuts in the leg mount itself, it is recommended to use power tools to tighten these components to reduce the time and effort spent on this single subassembly. The itemized list of assembly time for each subassembly can be seen in the DVPR table in Appendix Q. Although this test failed the criteria of 20 minutes by almost double the time, we do not expect the entire planarizer to ever be completely disassembled and reassembled as it was for this test. The main reason for why the planarizer would be disassembled would be for storage ease, but we expect that this planarizer will not need to be disassembled significantly to be stored conveniently. The recommended disassembly for storage would be to separate the planarizer into three separate components. The first component could be the leg-mount attached to the boom. This is separated from the rest of the planarizer by loosening the set screws in the metal shaft ends and pulling out both of the carbon fiber booms. The rest of the planarizer could be taken apart by unscrewing the base enclosure from the plywood. The second component will consist of the base enclosure, yoke, and DAQ mount, while the third component will consist of the base plate mounted onto the plywood.

8. *Project Management*

Our project management consisted of completing our initial prototype in CAD as well as the manufacturing and assembly plan for it. Then, we also completed analysis on the DAQ system sampling rate and the planarizer's velocity efficiency, which can be found in Appendix N: Encoder Selection Calculations and Appendix M: Velocity Efficiency, respectively. Notably, we also revised our entire base design to cope with larger stresses than the singular base post screw could handle and for ease of manufacturability. To continue staying on track, we then ensured that the drawings of our parts we plan to machine are within necessary tolerances and dimensioning by obtaining validation from Cal Poly Shop Techs at the Aero Hangar. Finally, our advisor approved our Design Verification Plan seen in Section 7 which took place after the prototype manufacturing and assembly were completed. Looking at our project in a larger scope, current key milestones for the final quarter of senior project and their respective due dates can be found below in Table 9.

Table 9. Key Milestones & Due Dates

Milestones	Due Date
Prototype Sign Off	March 9, 2022
Final Design Review	March 15, 2022
FDR Presentation to Sponsors	March 17, 2022

For more details of our schedule and how our timeline matched our goals, refer to the Gantt Chart below in Appendix I: Gantt Chart.

Looking back at our project management above, I think our process could be improved. We spent too much time manufacturing, especially on our original base plate which we ended up discarding due to manufacturing difficulties. This halted us at the end where we were pressed for time finishing our specification tests as well as this Final Design Review. In our next design project, we will ensure the manufacturability of all our components. Cast iron is much harder than steel which in turn is much harder than aluminum. Having engrained this fact would have led our design approach towards softer materials such as aluminum. As well, we will also buy our parts in bulk to streamline the purchasing and reimbursement process for our sponsor. Optimistically, our specialization worked well. We handled production based on personal skills where our group members excelled in mechatronics or manufacturing and modeling. This allowed us to focus on our respective tasks thus completing the many systems of our prototype simultaneously.

9. *Conclusion and Recommendations*

The Cal Poly Legged Robot Team is developing a quadruped robot, and they need a planarizer to accurately record the position of the robot leg and its dynamics. The task of prototyping this 2 degrees of freedom planarizer is outlined in this document through background research, customer specifications and objectives, concept design, and project management. We hope that our design will prove useful to the team, and that, if necessary, the content in this report will bridge the gap in knowledge for anyone that wants to reconsider or modify the planarizer design. To the ends of improving our design, we have some recommendations below.

9.1 Manufacturing Recommendations

There were many challenges in the production of our planarizer prototype. One of the more significant issues we came into was with the base plate. We chose a material that turned out to be significantly more difficult to machine than we had predicted. We spent about 15 hours in the shop, trying to drill and tap eight holes, which we were unable to complete. Drills had a lot of trouble trying to cut through it, where for the larger holes, we had a lot of difficulty getting material to come off, and for the smaller holes, the drills kept breaking inside the metal. Luckily, we were able to have Tim's family friend machine and assemble another design for us, which we proceeded with. If it is desired to use the previous design, then we recommend selecting a much softer material for the base plate. An arbitrary steel alloy was chosen for its price and weight. However, the machine time ended up making the part much more expensive than we had predicted.

9.2 Modeling Recommendations

One area where we could see significant improvement would be in the modeling of the velocity efficiency. We thought that the bearing drag would be negligible, so we neglected damping in the model. The drag, while not large, was noticeable and therefore should not have been neglected. We discovered this when we were performing the Velocity Efficiency Verification Test. To measure the moment of inertia we swung the Planarizer as a pendulum, but we were only able to obtain 6 to 10 oscillations. We expected much more, which suggests that the damping left more losses in the system than we desired. With damping incorporated into the model, the velocity efficiency verification test could be performed again, accounting for everything, which would give us a more accurate description of the Planarizer's dynamic effects. This would then allow for a better understanding of how the Planarizer loads the robot leg, and potentially allow the Cal Poly Legged Robots Team to make accurate predictions of how the leg would operate without the Planarizer.

9.3 DAQ Recommendations

As far as the DAQ goes, there are still issues, especially with how slow the polling rate is. This is likely the greatest area for improvement. With a higher polling rate, we can expect less uncertainty in the data as well as just simply more data. Some recommendations are discussed in the documentation for the DAQ. With the current hardware, rewriting the code using STM32CUBEMX may allow the polling rate to significantly increase. If possible, we highly recommend looking into slip rings that are designed for allowing sensor signals through, like servo slip rings, so that Bluetooth may be avoided. This would increase the overall data quality and possible data transmission rate. Some other improvements that could be made include creating a custom PCB for more reliable wired connections in a smaller form factor and replacing the constant load circuit that keeps the power bank on with a more power efficient pulsing load circuit.

References

[1] SEER Training Modules, *Module Name*. U. S. National Institutes of Health, National Cancer Institute. 20 April 2021 <*https://training.seer.cancer.gov/*>.

[2] J. S. Colett and J. W. Hurst, “Artificial Restraint Systems For Walking And Running Robots: An Overview,” *International Journal of Humanoid Robotics*, vol. 09, no. 01, p. 1250001, 2012.

[3] J. Ramos, Y. Ding, Y.-woo Sim, K. Murphy, and D. Block, “HOPPY: An open-source and low-cost kit for dynamic robotics education,” Oct. 2020.

[4] Zufferey, Jean-Christophe, and Garth Zeglin. “Bow Leg Hopper.” *The Robotics Institute Carnegie Mellon University*, Carnegie Mellon, 15 Mar. 2021, www.ri.cmu.edu/project/bow-leg-hopper/.

[5] Pratt, Jerry. *Spring Flamingo (1996-2000)*, Massachusetts Institute of Technology, www.ai.mit.edu/projects/leglab/robots/Spring_Flamingo/Spring_Flamingo.html.

[6] “MABEL the Bipedal Robot.” *Electrical and Computer Engineering*, University of Michigan, 16 Aug. 2011, ece.engin.umich.edu/stories/mabel-the-bipedal-robot.

[7] Greenwood, Veronique. “Meet Mabel: The Robot That Does a 9-Minute Mile.” *CBS News*, CBS Interactive, 17 Aug. 2011, www.cbsnews.com/news/meet-mabel-the-robot-that-does-a-9-minute-mile/.

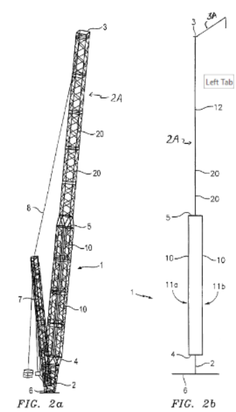
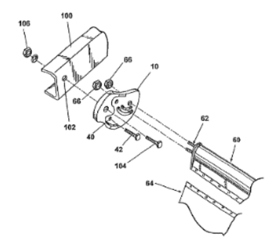
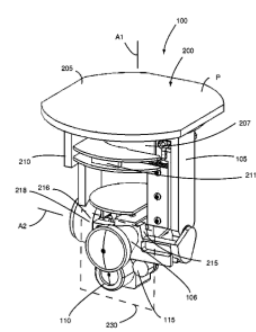
[8] A. Sato, “A Planar Hopping Robot with One Actuator: Design, Simulation, and Experimental Results,” Jun. 2004.

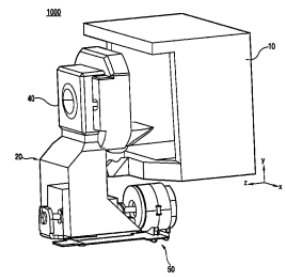
[9] I. Uyanik, “Identification of Legged Locomotion via Model-Based and Data-Driven Approaches,” May 2017.

[10] “E6 Optical Kit Encoder.” *US Digital®*, US Digital®, 2011, www.usdigital.com/products/encoders/incremental/kit/E6.

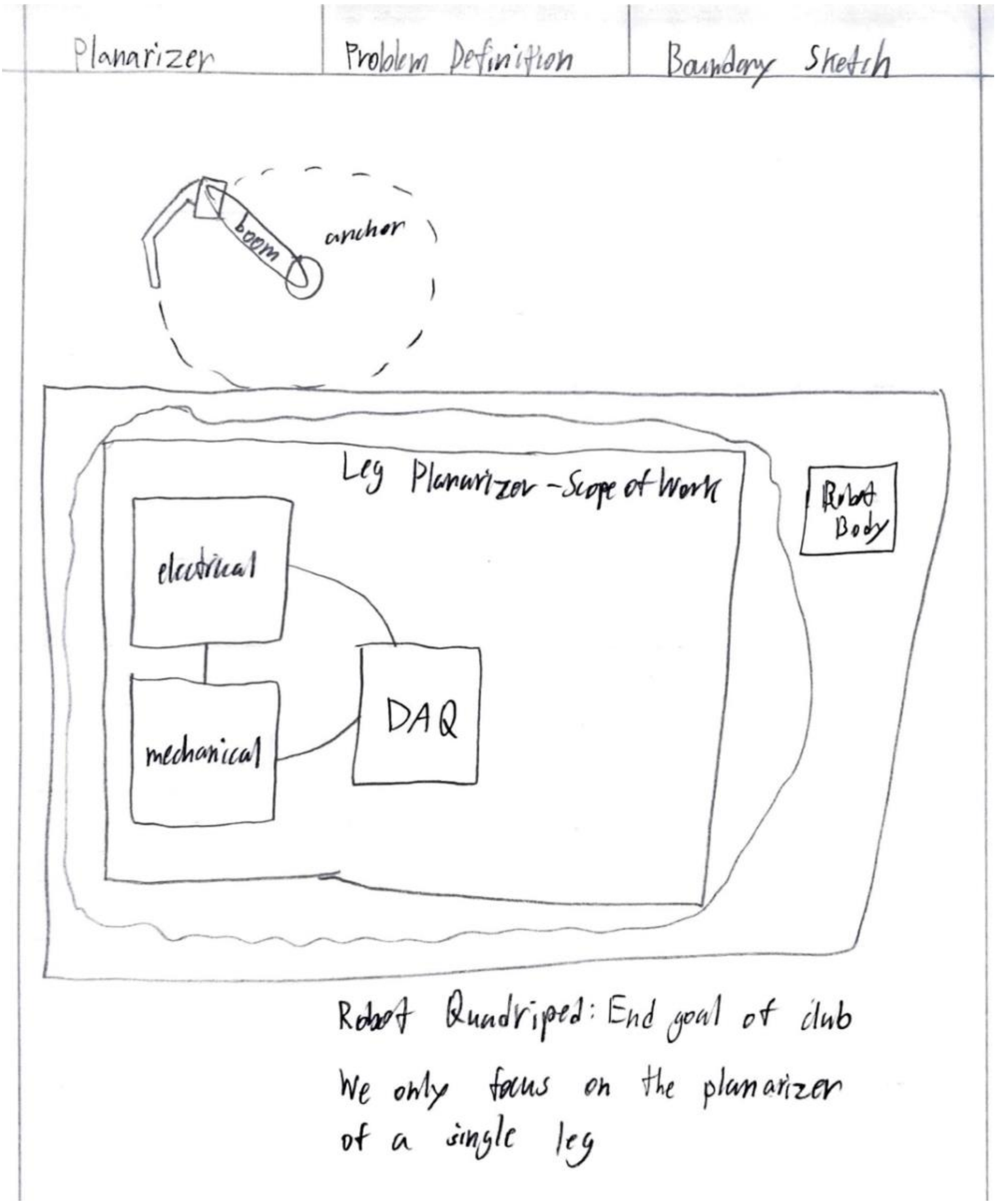
[11] “What Is Electrical Noise and How Does It Impact Your Encoder?” *How Does Electrical Noise Impact Your Encoder*, US Digital, 12 Dec. 2019, https://www.usdigital.com/blog/how-does-electrical-noise-impact-your-encoder/.

Appendix A: Patents

Patent Number	Patent Title	Description	Drawing
US8177081B2	Lattice Mast Crane and Lattice Mast Boom	The lattice mast boom consists of a plurality of lattice pieces releasably connectable with each other, a head piece, and a pivot piece. A great motivation for this patent is the need to reduce deflection of the tip of the boom due to side forces and buckling during luffing, cost of booms, and handle multiple different loads. The lattice mast boom also allows for ease of assembly/disassembly as well as a great deal of modularity.	
US6435462B2	Universal Bracket Mount	This invention relates to a universal mudflap bracket mount. It comprises a frame-mounting block and a bracket-mounting plate. Motivation for this invention comes from the difficulty that some consumers have when attempting to attach mudflaps to their vehicles. Some vehicles have obstructed the required holes or placed them in spots that owners may not desire. This mount attempts to adjust this by allowing for multiple mounting positions and allow for adjustability with the mudflap.	
US9435520B2	Gimbal System Providing High-Precision Imaging Capabilities In A Compact Form-Factor	Motivation for this invention comes from the need for a high precision gimbal system that provides a suitably high resolution of pointing accuracy. This is intended to help with delivering laser-guided ordinance. It implements a two-axis azimuth/inner elevation configuration, which was chosen for its lower weight when compared to other gimbal configurations.	

Patent Number	Patent Title	Description	Drawing
US9998669B2	Camera Gimbal	The camera gimbal is designed to maintain a horizontal posture through gravity. It is intended to be mounted onto an unmanned air vehicle (such as a drone) to allow for stable photography in flight. This invention aims to be cost effective, light, and compact in comparison to convention gimbals. The camera gimbal includes a gimbal barrel, a freely rotatable lens barrel to support a camera module, and a connection unit configured to connect the gimbal and lens barrels. It includes a rolling, yawing, and pitching axis for the lens barrel.	

Appendix B: Boundary Sketch



Appendix C: QFD House of Quality

Correlations	
Positive	+
Negative	–
No Correlation	

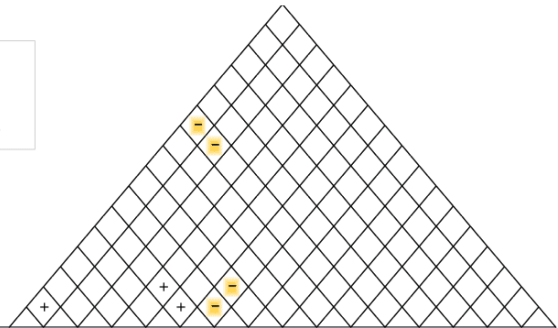
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Planarizer

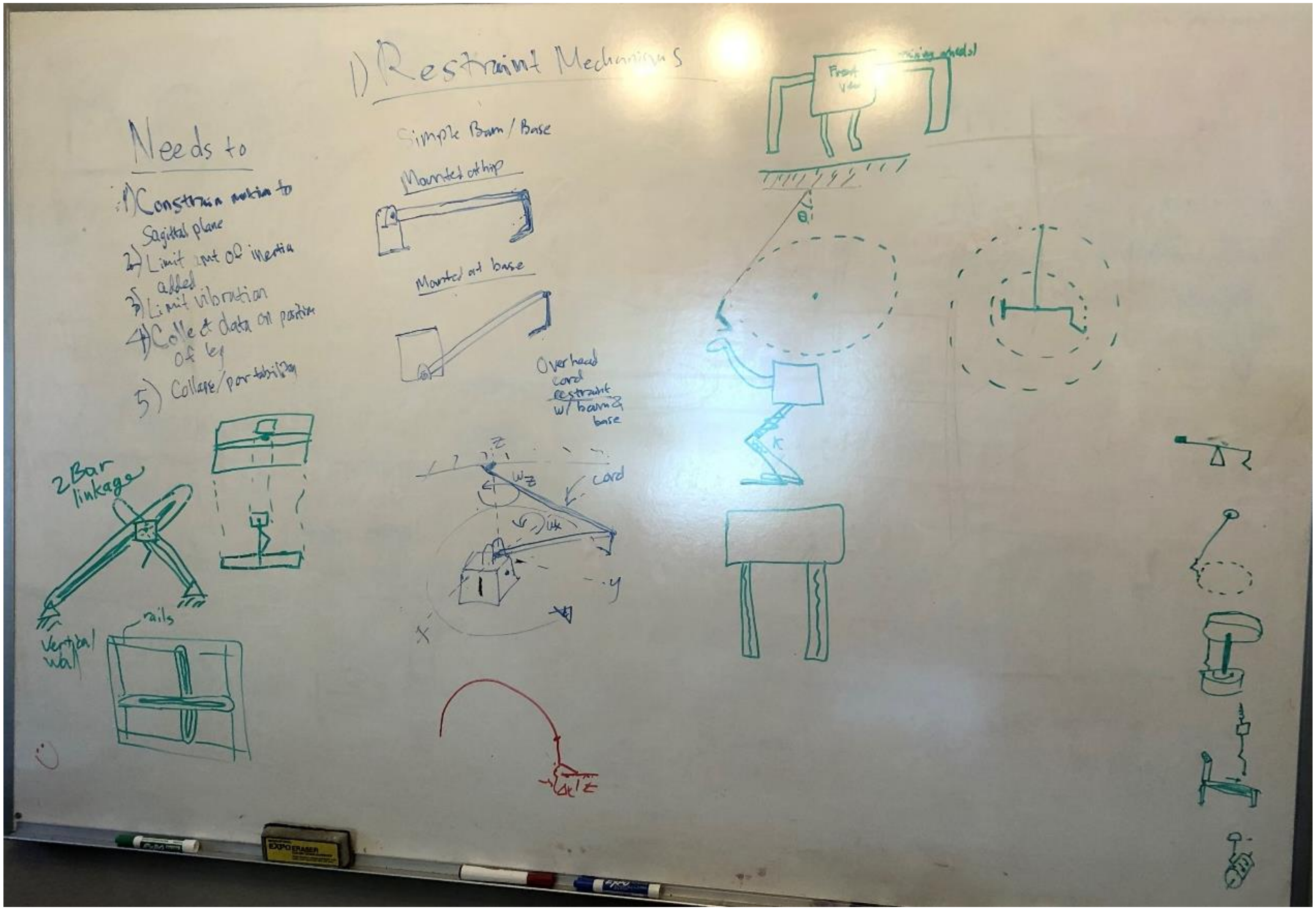
Revision Date: _05/23/21________________

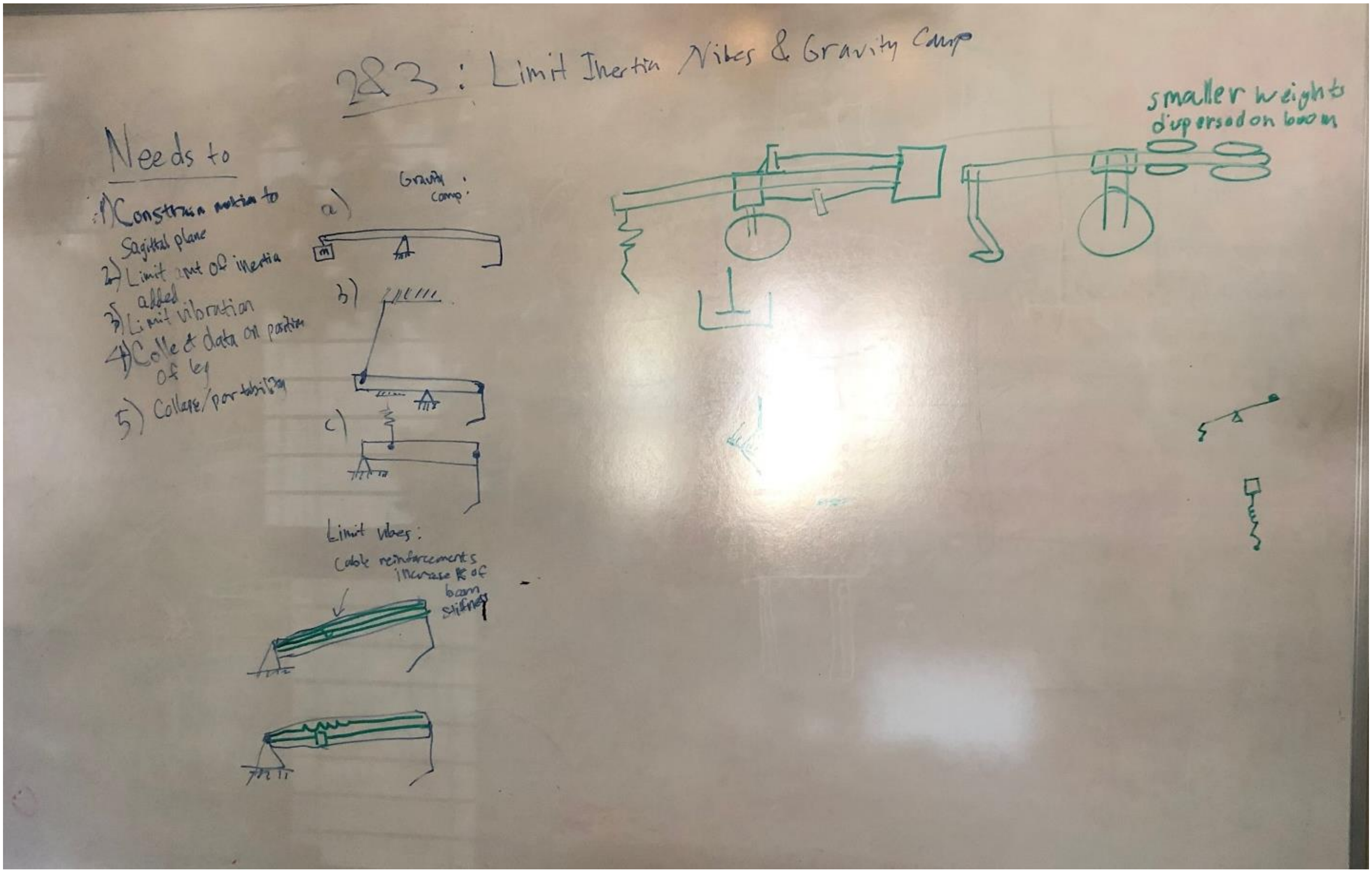


							Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
	WHO: Customers						Direction of Improvement	▼	▼	▲	▲	▼	▼	▼	▼	▼	▼	◇						NOW: Curr. Products					
Row #	Weight Chart	Relative Weight	Cal Poly Legged Robot Team	Manufacturing			Maximum Relationship	HOW: Engineering Specifications (Tests) / WHAT: Customer Requirements (Needs/Wants)	Apparent Mass Increase	Apparent Mass Moment of Iner	Yaw Path Deviation	Sampling Rate	Data Resolution	Cost	Absolute Tip Deflection	Upload Time	Assembly Time	Allowable Leg Mass	Operating Leg Speeds						Our Current Product	Competitor #1:HOPPY	Competitor #2: BowLeg Hopper	Competitor #3: Spring Flamingo	Competitor #4: MABEL	Row #
1		18%	8	7			9	Good Data			▽	●	●		○	●		○	○						0	4	3	2	4	1
2		18%	10	5			9	Limited Dynamic Effects	●	●	●		○	○	●			○							0	4	4	3	4	2
3		15%	6	6			9	Collapsable/Portable	○	○				○	○		●								0	3	2	1	1	3
4		17%	9	5			9	User Friendly				○	●		○	●	○								0	4	3	3	3	4
5		15%	6	6			9	Versatility	○	○								●	●						0	3	3	3	4	5
6		18%	5	9			9	Affordable	○				○	●											0	4	3	2	1	6
7		0%																												7
8		0%																												8
9		0%																												9
10		0%																												10
11		0%																												11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

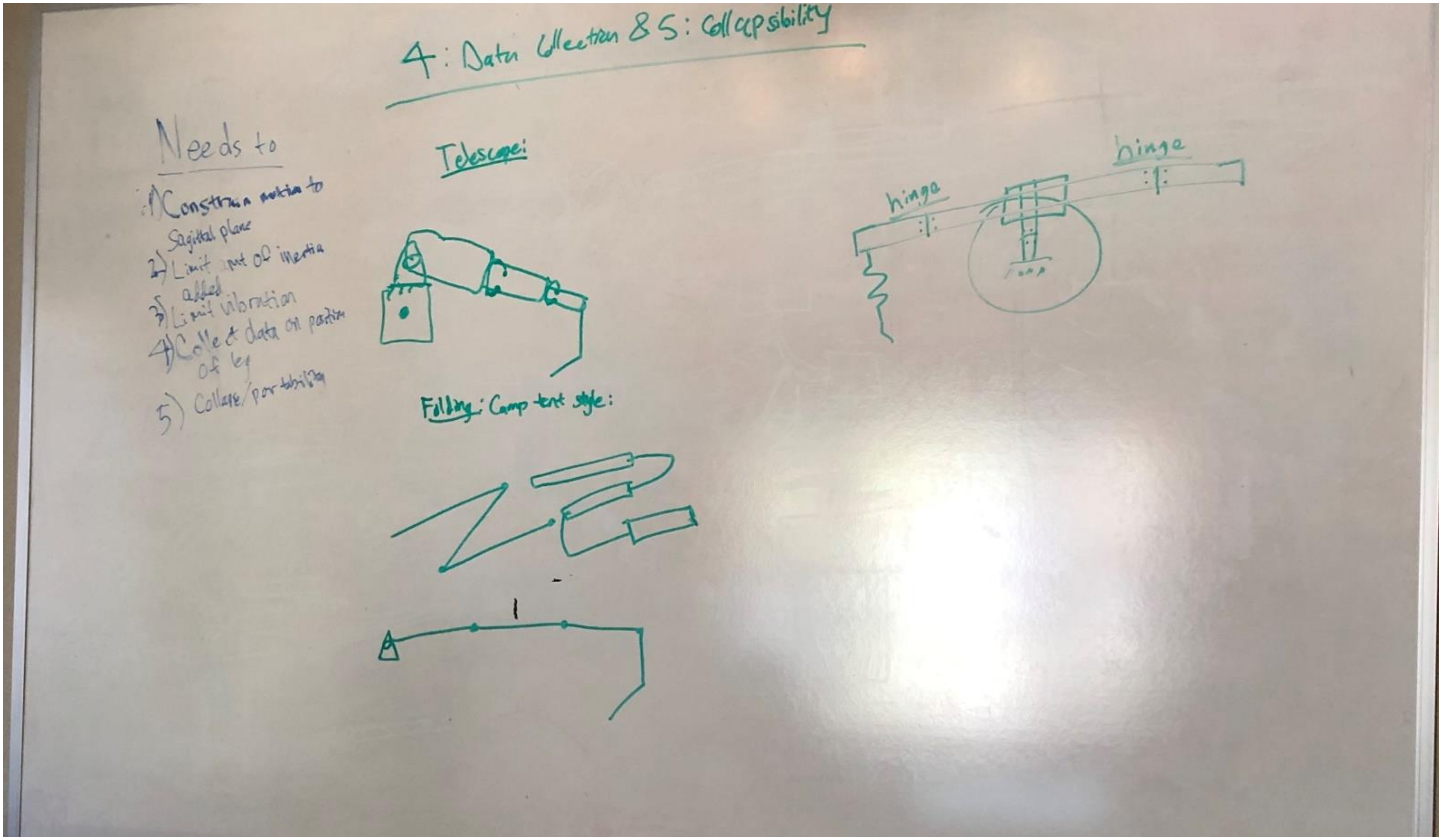
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	0.25 kg	0.25 kg-m^2	5 deg per hop	200 Hz	1 mm	$1,000	0.01 mm	15 seconds	20 minutes	1.25 kg	2 m/s					
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9					
	Technical Importance Rating	302	250	180	215	422	256	311	316	183	241	187	0	0	0	0	0
	Relative Weight	11%	9%	6%	8%	15%	9%	11%	11%	6%	8%	7%	0%	0%	0%	0%	0%
Curr. Products	Our Current Product	0	0	0	0	0	0	0	0	0	0	0					
	Competitor #1:HOPPY	3	3	5	4	4	5	4	4	4	5	4					
	Competitor #2: BowLeg Hopper	3	0	4	5	3	2	2	4	5	4	4					
	Competitor #3: Spring Flamingo	4	1	5	4	4	2	2	4	4	2	2					
	Competitor #4: MABEL	1	5	2	1	1	1	2	4	1	1	2					
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Appendix D: Ideation Processes



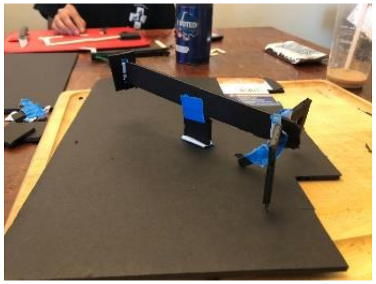


2&3 : Limit Inertia Vibes & Gravity Comp
Needs to
1) Constrain motion to Sagittal plane
2) Limit amt of inertia added
3) Limit vibration
4) Collect data on position of leg
5) Collapse/portability
Gravity comp:
a)
m
b)
c)
Limit vibes:
Cable reinforcements increase k of beam stiffness
smaller weights dispersed on boom

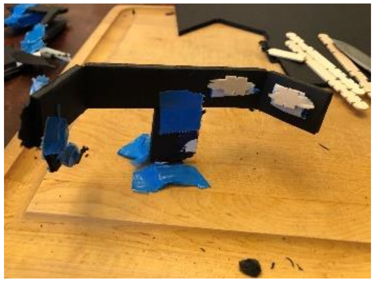

4: Data Collection & 5: Collapsibility
Needs to
1) Constrain motion to Sagittal plane
2) Limit amt of inertia added
3) Limit vibration
4) Collect data on position of leg
5) Collapse/portability
Telescope:
Folding: Camp tent style:
hinge
hinge

Ideation Models

Design 1: "Training wheels" attached to boom for sagittal stability, more inertia outside axis of rotation



Design 2: Hinged assembly with three folds for portability

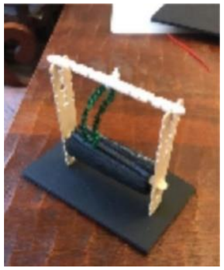


Design 3: Boom attached to hip of leg, cord attached to ceiling

Design 4: Boom with counterweight, similar to HOPPY

Design 5: Leg held up from above with spring, treadmill to maintain leg's speed

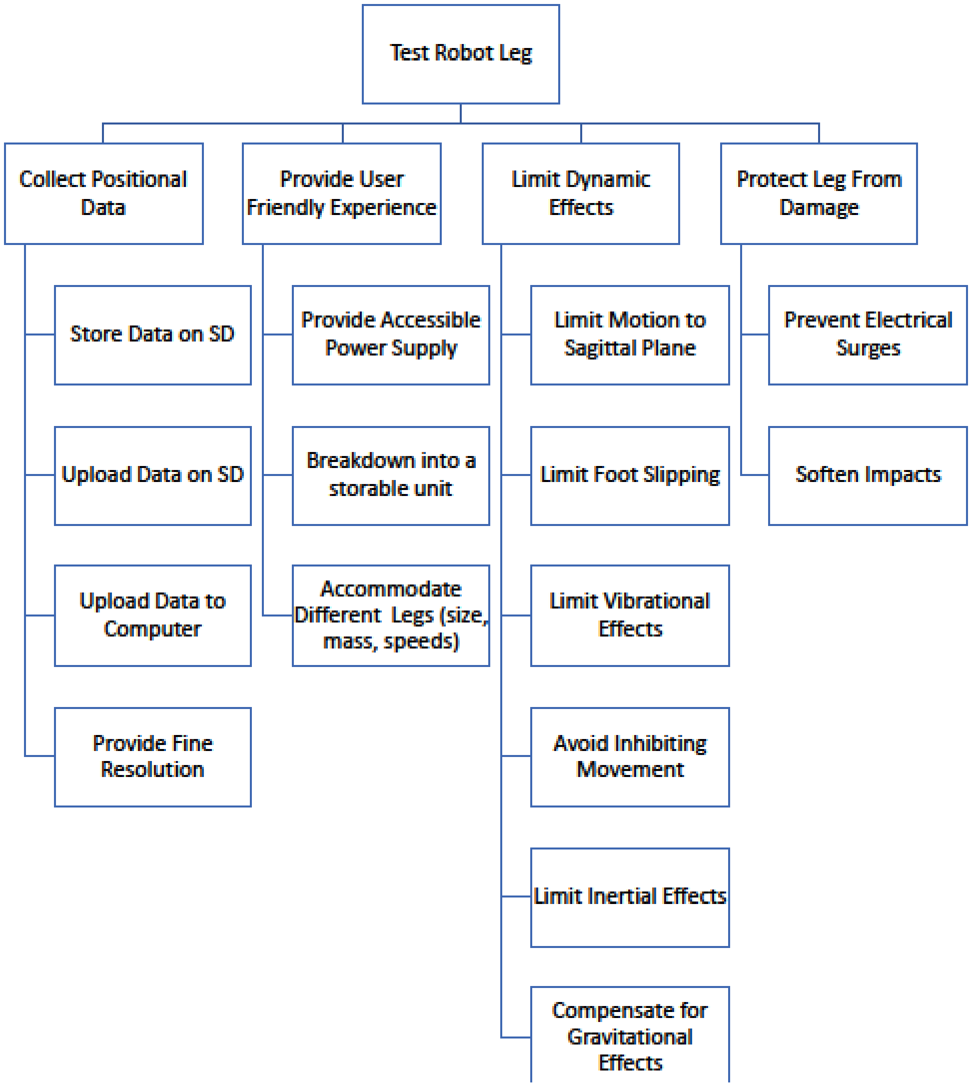
Design 6: leg constrained from above, with rolling cylinder to keep leg in place as it goes into motion



Design 7: Boom with electronics assembly at post, boom is attached to hip of leg

Design 8: Two bar linkage, with robot attached at hip, and treadmill to provide continuous motion

Appendix E: Functional Decomposition

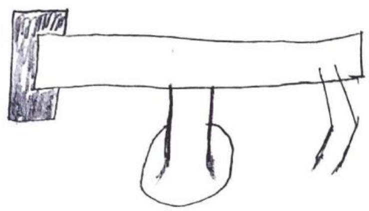


Appendix F: Pugh Matrices

Matthew Wimberley | ME428 | Pugh Matrix

Ideation Models

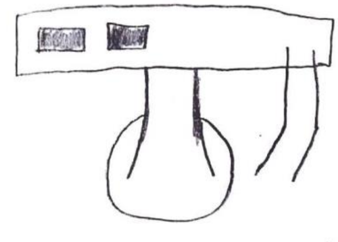
1



This is the basic boom-base apparatus. The counterweight is a single piece meant to counteract leg weight on opposing side.

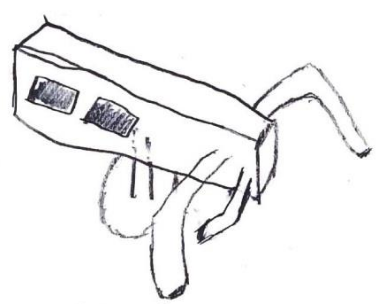
This model inspired #2.

2



The shaded part is the counterweight, now in two separate pieces along the length of the shaft. Better suited for rotary dynamics.

3

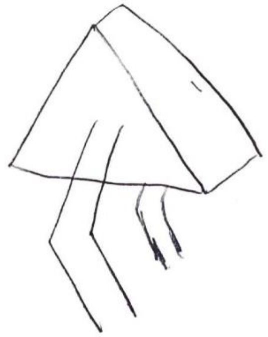


This model has "training wheels" for stability along sagittal plane. More stable but more inertial forces acting away from COG (center of gravity)

4

To make a more portable model, I gave the boom hinges. There are three folds on this assembly that let it be more compact.

5



This last one is just a concept model for bipedal movement, like an AT-ST Walker. Maybe once one leg is stable we can move on to more.

MW | ME428

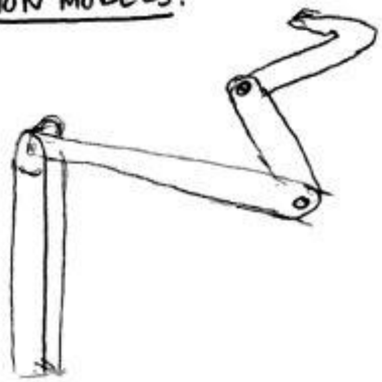
Criteria \ Model	1	2	3	4	5
Boom Mass 0	−	S	S	+	+
Yaw Deviation 0	−	+	+	−	+
Assembly Time 0	S	S	−	+	+
Boom Tip Deflection 0	−	−	+	S	−
Boom Vibration 0	−	S	−	S	−
Portability 0	S	S	−	+	−
Catch Mechanism 0	+	+	+	−	S
Protect encoder 0	+	+	S	−	+
"Wow Factor" 0	S	+	+	S	−
Total 0	-2	3	1	0	0

☆

TIM JAIN	ME 428	PUGH MATRIX

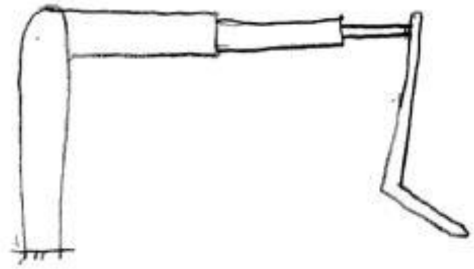
IDEATION MODELS:

(1)



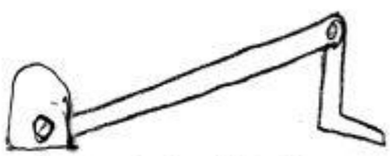
PIN CONNECTED AT MIDDLE SO THAT BOOM CAN BE COLLAPSED AND STORED EASILY

(2)



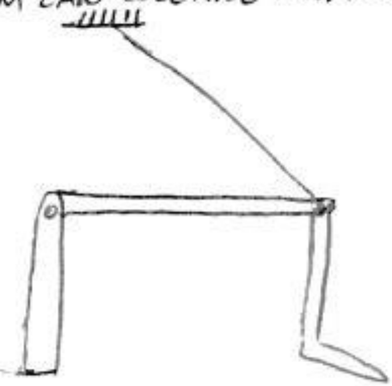
TELESCOPING BOOM: DIFFERENT SHAFT DIAMETERS SO THAT BOOM CAN COLLAPSE INWARD

(3)



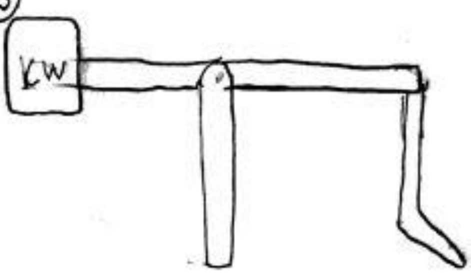
BOOM ATTACHED TO BASE OF BOOM. THIS IS DONE TO LIMIT THE AMT OF FOOT SLIP

(4)



SIMPLE BOOM ATTATCHED AT TOP OF BASE TO ALIGN W/ HIP OF LEG. THE CORD IS ATTACHED AT THE END OF BOOM, WHICH IS THEN ATTACHED TO CEILING

(5)



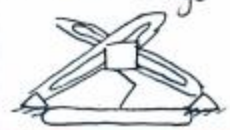
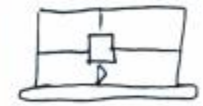
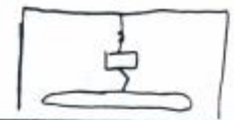
BASE AT CENTER OF BOOM. COUNTERWEIGHT PLACED AT END OF BOOM TO LIMIT EFFECTS OF WEIGHT OF BOOM

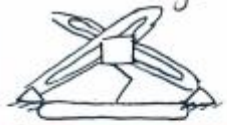
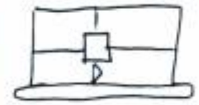
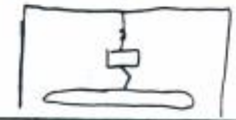
TIM JAIN | ME 428 | PUGH MATRIX

IDEATION MODELS:

Criteria \ Model	1	2	3	4	5
Boom Mass	+	–	+	–	S
Yaw Deviation	–	–	+	+	S
Assembly Time	+	–	+	S	–
Boom Tip Deflection	–	–	S	+	+
Boom Vibration	–	–	S	+	+
Portability	+	+	S	–	S
Catch Mechanism	–	–	–	+	–
Protect Electronics	–	–	–	–	S
"Wow Factor"	+	+	–	+	S
Limited Dynamic Effects	–	–	S	+	S
Total	-2	-6	0	3	0

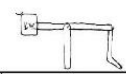
					
approaches sagittal	+	-	-	s	+
affordable	+	+	-	s	-
portable	s	+	-	+	-
limits inertial effects	-	-	+	+	+
total	1	0	-2	2	0
rank	2	3	4	1	3

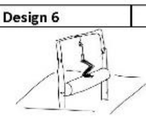
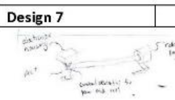
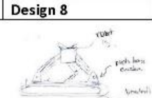
Concept / Criteria	1. Boom/Base 	2. 2-Bar Linkage 	3. Linear Bearings & Rails 	4. Overhead Gantry 
Limited Dynamic Effects	S	–	–	+
Portable	+	+	–	–
Versatile	S	–	–	S
Affordable	+	–	–	–
Σ^+	2	1	0	1
Σ^-	0	0	4	2
Σ^S	2	0	0	1
Total	2	1	-4	-1
	☆	☆		

Concept / Criteria	1. Boom/Base 	2. 2-Bar Linkage 	3. Linear Bearings & Rails 	4. Overhead Gantry 
Limited Dynamic Effects	S	−	−	+
Portable	+	+	−	−
Versatile	S	−	−	S
Affordable	+	−	−	−
$\sum^{+}$	2	1	0	1
$\sum^{-}$	0	0	4	2
$\sum^{S}$	2	0	0	1
Total	2	1	-4	-1
	★	★		

Appendix G: Decision Matrix

Team Planarizer Weighted Decision Matrix

		Design 1		Design 2		Design 3		Design 4	
									
		"Training wheels" attached to boom for sagittal stability, more inertia outside axis of rotation		Hinged assembly with three folds for portability		Boom attached to hip of leg, cord attached to ceiling		Boom with counterweight, similar to HOPPY	
Criteria	**Weighting**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Apparent Mass Increase	0.16	1	0.164179	3	0.492537	4	0.656716	1	0.164179
Apparent Mass Moment of Inertia Increase	0.13	1	0.134328	3	0.402985	4	0.537313	1	0.134328
Path Deviation	0.09	3	0.268657	1	0.089552	3	0.268657	3	0.268657
Cost	0.13	2	0.268657	3	0.402985	4	0.537313	3	0.402985
Data Quality	0.16	4	0.656716	2	0.328358	4	0.656716	2	0.328358
Assembly Time	0.09	3	0.268657	5	0.447761	2	0.179104	4	0.358209
Allowable Mass	0.12	1	0.119403	2	0.238806	3	0.358209	1	0.119403
Operating Speeds	0.10	3	0.313433	3	0.313433	2	0.208955	2	0.208955
Grand Total	1.00		2.19403		2.716418		3.402985		1.985075

		Design 5		Design 6		Design 7		Design 8	
									
		leg held up from above with spring, treadmill to maintain leg's speed		leg constrained from above, with rolling cylinder to keep leg in place as it goes into motion		Boom with electronics assembly at post, boom is attached to hip of leg		Two bar linkage, with robot attached at hip, and treadmill to provide continuous motion	
Criteria	**Weighting**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**	**Score**	**Total**
Apparent Mass Increase	0.16	5	0.820896	5	0.820896	4	0.656716	2	0.328358
Apparent Mass Moment of Inertia Increase	0.13	5	0.671642	5	0.134328	4	0.537313	2	0.268657
Path Deviation	0.09	1	0.089552	1	0.089552	3	0.268657	5	0.447761
Cost	0.13	1	0.134328	2	0.268657	4	0.537313	1	0.134328
Data Quality	0.16	1	0.164179	1	0.164179	4	0.656716	5	0.820896
Assembly Time	0.09	1	0.089552	1	0.089552	3	0.268657	2	0.179104
Allowable Mass	0.12	5	0.597015	5	0.597015	3	0.358209	2	0.238806
Operating Speeds	0.10	5	0.522388	3	0.313433	2	0.208955	5	0.522388
Grand Total	1.00		3.089552		2.477612		3.492537		2.940299

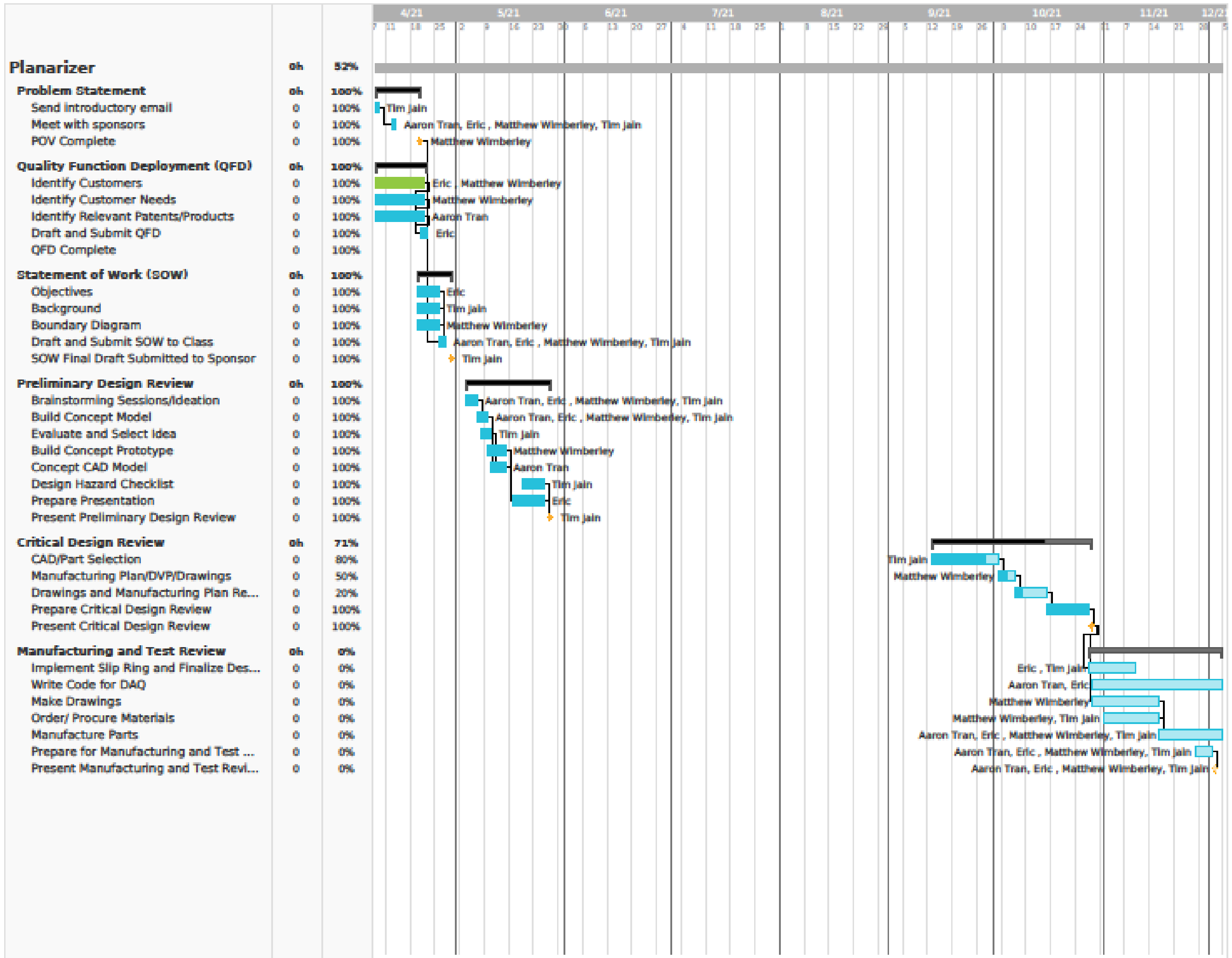
Appendix H: Design Hazard Checklist

PDR Design Hazard Checklist **Planarizer**

Y	N	
	X	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
	X	5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
	X	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?
	X	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

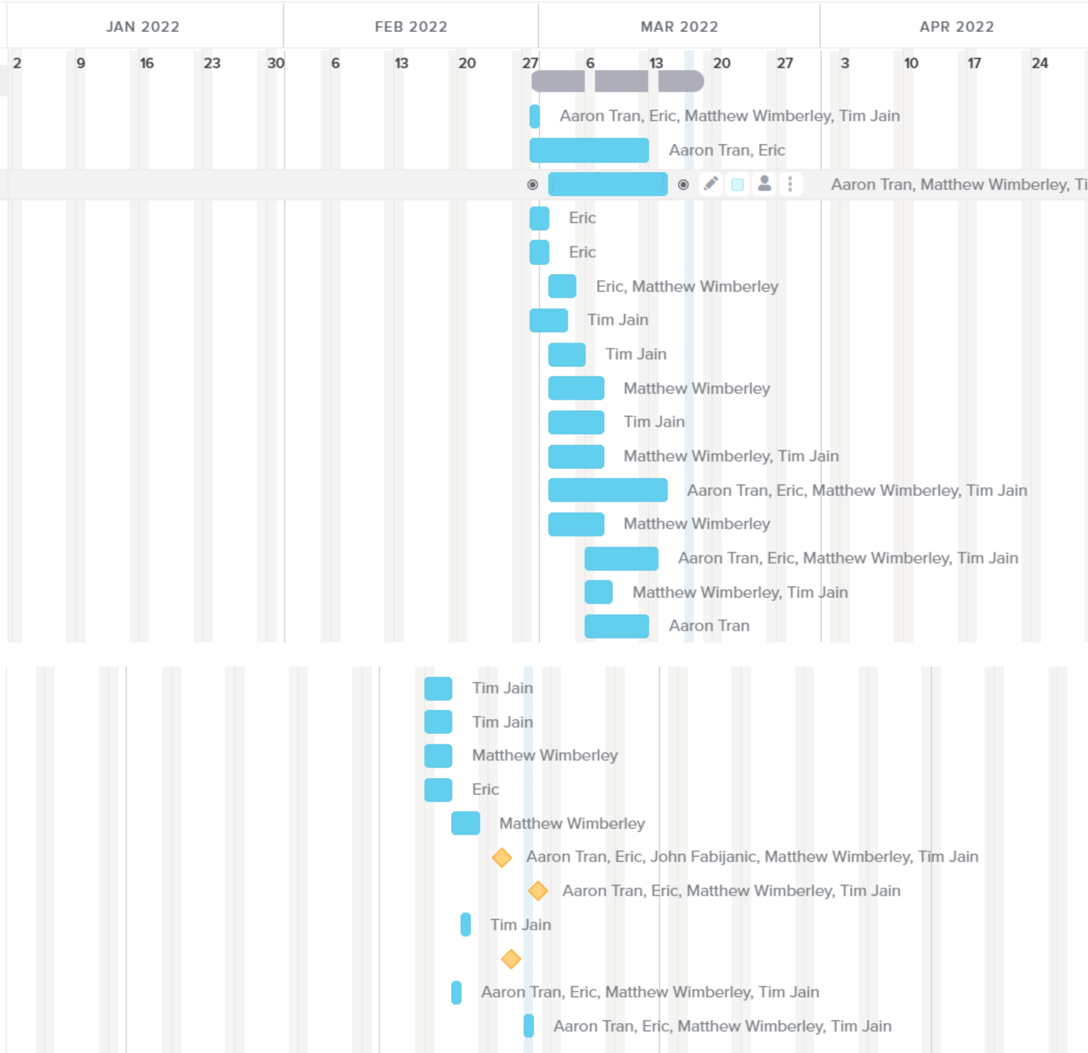
Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
Use of Battery, potentially flammable	Use a battery with small voltage (~9V) to limit dangerous effects in case of overheating, battery terminal covers will prevent short circuits due to poor storage	Fall 2021	
System used in unsafe manner (if user stands in the path of the boom while rotating)	Place warning stickers to tell user to stand away from the system while in operation	Fall 2021	

Appendix I: Gantt Chart



Spring and Fall Quarters

	Assigned	Progress
▾ Final Design Review		100%
Mass Moment of Inertia Test	Aaron Tran, Eric, Ma	100%
DAQ Test	Aaron Tran, Eric	100%
Document Our Testing Procedur...	Aaron Tran, Matthev	100%
Schedule Verification Prototype Signoff	Eric	100%
Schedule Testing Signoff	Eric	100%
Finish User Manual	Eric, Matthew Wimb	100%
Schedule FDR Presentation	Tim Jain	100%
Add disclaimer page to FDR	Tim Jain	100%
Update Abstract, Intro, Background, & Obje...	Matthew Wimberley	100%
Update Final Design	Tim Jain	100%
Update Manufacturing	Matthew Wimberley	100%
Update Design Verification	Aaron Tran, Eric, Ma	100%
Update Project Management	Matthew Wimberley	100%
Complete Conclusions and Recommendatio...	Aaron Tran, Eric, Ma	100%
Complete Drawing Package	Matthew Wimberley	100%
Appendix: Wiring Diagrams, Flowcharts, Soft...	Aaron Tran	100%
Appendix: Brief Product Specs	Tim Jain	100%
Appendix: Final Project Budget	Tim Jain	100%
Update FMEA and Design Hazard Checklist	Matthew Wimberley	100%
Update Risk Assessment	Eric	100%
Completed Gantt Chart	Matthew Wimberley	100%
Submit FDR to Advisor	Aaron Tran, Eric, Joh	☑
Present FDR	Aaron Tran, Eric, Ma	☑
Send Option C Resimbursement Form	Tim Jain	100%
Submit FDR to Library		☑
Verification Prototype and Testing Sign Off	Aaron Tran, Eric, Ma	100%
Clean Out Bonderson	Aaron Tran, Eric, Ma	100%

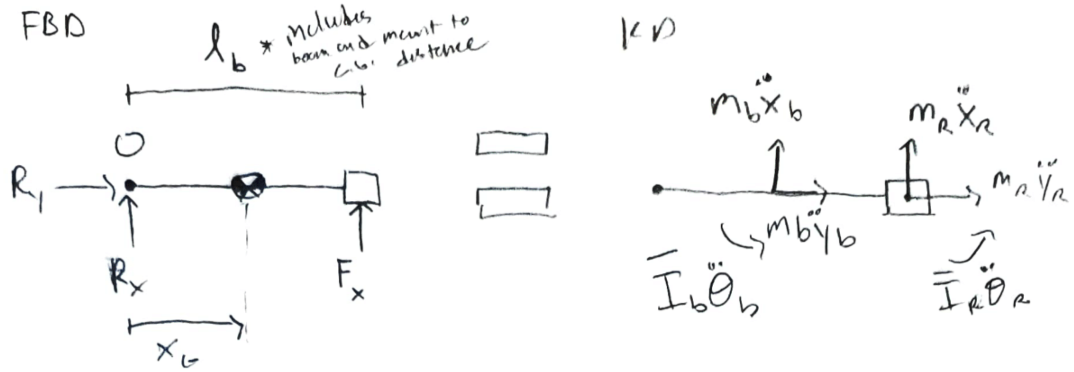


Winter Quarter

Appendix J: Yaw Motion Dynamic Analysis

Assume all force is in tangential direction, boom is rigid

FBD KD



FBD = KD

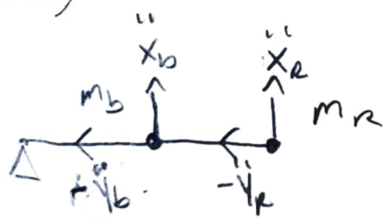
$$+\circlearrowleft \Sigma M_o: \; F_x l_b = \bar{I}_b\ddot{\theta}_b + x_G m_b\ddot{x}_b + \bar{I}_R\ddot{\theta}_R + l_b m_R\ddot{x}_R$$

Kinematics:
Rotational

$\dot{\theta}_b, \ddot{\theta}_b$

Since bar is rigid:

$$\dot{\theta}_b = \dot{\theta}_R$$
$$\ddot{\theta}_b = \ddot{\theta}_R$$



$$\ddot{x}_b = \ddot{\theta}_b x_G \quad , \quad \ddot{x}_R = \ddot{\theta}_R l_b$$

$$\underline{\ddot{y}_b = -\dot{\theta}_b^2 x_G \quad , \quad \ddot{y}_R = -\dot{\theta}_R^2 l_b}$$

$$\hookrightarrow \ddot{x}_b = \frac{x_G}{l_b}\ddot{x}_R , \; \ddot{y}_b = \frac{x_G}{l_b}\ddot{y}_R$$

Return to ΣM_o equation:

$$F_x l_b = \bar{I}_b \cancel{\ddot{\theta}_b}^{\,\ddot{\theta}_R} + x_G m_b \cancel{\ddot{x}_b}^{\,\frac{x_G}{l_b}\ddot{x}_R} + \bar{I}_R\ddot{\theta}_R + l_b m_R\ddot{x}_R$$

$$F_x l_b = (\bar{I}_b + \bar{I}_R)\ddot{\theta}_R + \left(\frac{x_G^2}{l_b} m_b + l_b m_R\right)\ddot{x}_R$$

$$+\circlearrowleft \sum M_P: \; F_x r_{CG} = \bar{I}_R\ddot{\theta}_R + m_R\ddot{x}_R r_{CG}$$

let $\ddot{\underline{q}} = \begin{bmatrix} \ddot{x}_R \\ \ddot{\theta}_R \end{bmatrix}$

$$M\ddot{\underline{q}} = \underline{f}$$

$$\begin{bmatrix} \frac{x_{CG}^2}{l_b} m_b + l_b m_R & \bar{I}_b + \bar{I}_R \\ m_R r_{CG} & \bar{I}_R \end{bmatrix} \begin{bmatrix} \ddot{x}_R \\ \ddot{\theta}_R \end{bmatrix} = \begin{bmatrix} F_x l_b \\ F_x r_{CG} \end{bmatrix}$$

$$\ddot{\underline{q}} = M^{-1}\underline{f}$$

$$\begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} = \frac{F_x}{I_R l_b^2 m_R + I_R m_b x_{CG}^2 - I_b l_b m_R r_{CG}^2 - I_R l_b m_R r_{CG}} \begin{bmatrix} I_b(I_b r_{CG} - I_R l_b + I_R r_{CG}) \\ m_b r_{CG} x_{CG}^2 \end{bmatrix}$$

Issues:

assume $m_b, I_b \approx 0$ (negligible inertial effect from planarizer)

then: $$\begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} = \frac{F_x}{I_R l_b^2 m_R - I_R l_b m_R r_{CG}} \begin{bmatrix} 0 \\ 0 \end{bmatrix} \Rightarrow \begin{bmatrix} \ddot{x} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

We do not believe that a lack of inertial effect from the planarizer should result in no leg acceleration

Appendix K: Dynamic Analysis

Team Planarizer – Dynamic Analysis

Author: Aaron Tran

Date Created: 05/11/21

Last Modified: 05/25/21

The following code is responsible for decoupling the dynamic equations developed to describe the motion of a robot leg constrained by a boom base planarizer. Motion is only considered in a 2D plane viewed from the top. The final matrix determined, g, is a vector consisting of the tangential acceleration of the robot leg, and the angular acceleration of the robot leg.

```
x_G          = sym('x_G', {'real', 'positive'});
m_b          = sym('m_B', {'real', 'positive'});
m_R          = sym('m_R', {'real', 'positive'});
l_b          = sym('l_b', {'real', 'positive'});
r_CG         = sym('r_CG', {'real', 'positive'});
I_r          = sym('I_r', {'real', 'positive'});
I_b          = sym('I_b', {'real', 'positive'});
F_x          = sym('F_x');
theta_ddot_r= sym('theta_ddot_r');
x_ddot_r     = sym('x_ddot_r');
eqn1 = F_x*l_b == (I_b + I_r)*theta_ddot_r + (x_G^2/l_b * m_b +
l_b*m_R)*x_ddot_r;
eqn2 = F_x*r_CG == I_r*theta_ddot_r +m_R * x_ddot_r*r_CG;
[M,f] = equationsToMatrix([eqn1;eqn2], [x_ddot_r, theta_ddot_r]);
g = M\f
```

g =

$$\begin{pmatrix} -\dfrac{F_x\, l_b\, (I_b\, r_{\mathrm{CG}} - I_r\, l_b + I_r\, r_{\mathrm{CG}})}{I_r\, {l_b}^2\, m_R + I_r\, m_B\, {x_G}^2 - I_b\, l_b\, m_R\, r_{\mathrm{CG}} - I_r\, l_b\, m_R\, r_{\mathrm{CG}}} \\ \dfrac{F_x\, m_B\, r_{\mathrm{CG}}\, {x_G}^2}{I_r\, {l_b}^2\, m_R + I_r\, m_B\, {x_G}^2 - I_b\, l_b\, m_R\, r_{\mathrm{CG}} - I_r\, l_b\, m_R\, r_{\mathrm{CG}}} \end{pmatrix}$$

Appendix L: Report Edit Log (PDR to CDR)

Report Section #	Source of recommended edit (Sponsor, Advisor, Team, Reviewer)	Brief description of edit
3.5	Sponsor & Advisor	'Horizontal deviation' changed to 'yaw path deviation' for added clarity
3.5	Reviewer	Font changed from Times New Roman to Calibri for consistency
3.5	Advisor	'Operating Speeds' changed to 'Operating Leg Speed'
3.5.12	Sponsor	Wording changed from 'at least' to 'up to' speeds of 2 m/s. 2 m/s is fast according to Dr. Xing, and we do not need to be operating that fast
3.5	Advisor	'Allowable Mass' changed to 'Allowable Leg Mass'. Changed tolerance from Max to Min
3.5	Advisor	Targets for Boom Mass and Boom Mass Moment of Inertia changed to TBD, since the mass of the robot leg is unknown
3.5.1	Advisor	Initial estimate for mass of boom given based on mass of leg
3.5.2	Advisor	Initial estimate for mass moment of inertia of boom given based on mass moment of inertia of leg
3.5	Advisor	'Boom Flexure' changed to 'Boom Tip Deflection' to clarify we are concerned with bending
3.5.7	Advisor	Clarified this spec is due to bending
2.1.1	Sponsor	Estimated jumping height changed to 800 mm, double the body height
2.3.4	Sponsor	Increase Data Acquisition Speed to 200 Hz, updated from 60 Hz
2.3.1.3	Sponsor	Address why we did not choose this rectangular coordinate system to define sagittal plane, with regards to potentiometers and encoders
3.2	Sponsor	Move "catch mechanism" from a Want to a Need, to reduce damage when falling
2.2.1	Sponsor	Mentioned Wanting the planarizer to be able to hop in a circle for sagittal approximation of leg dynamics
3.5.12	Sponsor	Leg does not need to operate at 2 m/s, actual value to be decided but needs to be stable most importantly
3.5.5	Advisor	Specified the directions in which we are interested in for data resolution
3.2	Sponsor	Add: Manage cables, so they do not become tangled to Want
4.7	Sponsor	Added: impact of boom vibration into data resolution

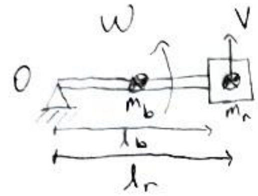
Appendix M: Velocity Efficiency

Top-down view dynamics

① Robot, unassisted

$$KE = \frac{1}{2} m_r v_r^2$$

② Robot w/ Plananizer



$$KE = \frac{1}{2} I_o \omega^2$$
$$= \frac{1}{2}\left[\bar{I}_b + m_b\left(\frac{l_b}{2}\right)^2 + \bar{I}_r + m_r l_r^2\right]\left(\frac{V}{l_r}\right)^2$$
$$= \frac{1}{2}\left(\frac{\bar{I}_b}{l_r^2} + \frac{m_b l_b^2}{4 l_r^2} + \frac{\bar{I}_r}{l_r^2} + m_r\right) V^2$$

Assume $KE)_{①} = KE)_{②}$ (insignificant damping or PE storage)

$$\cancel{\tfrac{1}{2}} m_r V_r^2 = \cancel{\tfrac{1}{2}}\left(\frac{\bar{I}_b}{l_r^2} + \frac{m_b l_b^2}{4 l_r^2} + \frac{\bar{I}_r}{l_r^2} + m_r\right) V^2$$

$$\eta_{vel} = \frac{V}{V_r} = \sqrt{\frac{m_r}{\frac{\bar{I}_b}{l_r^2} + \frac{m_b l_b^2}{4 l_r^2} + \frac{\bar{I}_r}{l_r^2} + m_r}}$$

$\equiv$ "velocity efficiency"

Appendix N: Encoder Selection Calculations

Encoder Selection

(1) $\Delta_{max} < \frac{PER}{2}$ ~ equation to ensure no error due to overflow when using ~~encoder~~

$\Delta_{max} \equiv$ maximum change in encoder ticks in between sampling

↳ $\Delta_{max} = \omega_{max} \cdot t$, where:

ω_{max} = maximum speed that is input into encoder

t = time between samples being taken

Sampling rate: 200 Hz

↳ $t = \frac{1}{200 Hz} = 0.005$ sec

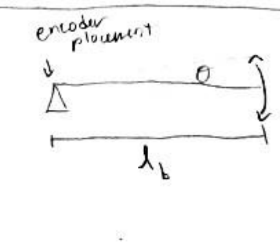
ω_{max} [ticks/sec] $= \omega_{max}$ [RPM] $\cdot$ PPR $\cdot \left(\frac{1 min}{60 sec}\right)$

PER:
Taken to be 0xFFFF for use on μPython $= 65{,}535$ ticks

ω_{max} [ticks/sec] $\cdot t < \frac{65{,}535 \text{ ticks}}{2}$

ω_{max} [RPM] $\cdot$ PPR $\cdot \left(\frac{1 min}{60 sec}\right) \cdot 0.005 sec < \frac{65{,}535 \text{ ticks}}{2}$

$$\boxed{PPR < \frac{393210000}{\omega_{max} [RPM]} \left[\frac{ticks}{Rev}\right]}$$

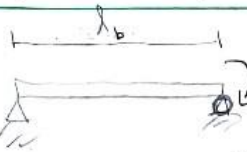


angular resolution of encoder:
$\theta_{res} = \frac{2\pi}{PPR}$

curvilinear resolution of beam tip:
$\boxed{s_{res} = l_b \theta_{res} = l_b \frac{2\pi}{PPR}}$

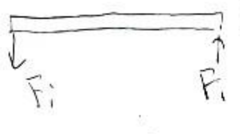
Appendix O: Vibrational Analysis

Vibrational analysis



$M_i \equiv$ Moment on boom due to impact

$F_i \equiv$ Force on beam due to impact



$$M_i = l_b F_i$$

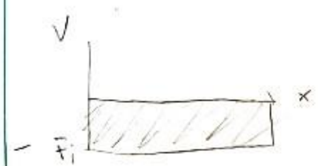
Reasoning for modeling:

On impact there are two contact points, one at the boom and one at the robot leg. We know that the "post" side allows for free rotation, so it cannot transmit a moment. Due to the nature of the boom to robot leg joint, relative rotation is restricted. We then treat this restriction as the load (a moment). Linear translation is also restricted, so we make use of a wheel restraint.

So:

- we assume that there is an instant where the load is transmitted using a moment and that the system is static at impact.

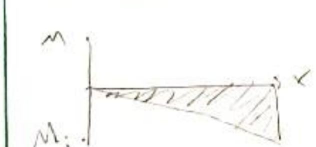
Analysis:



$$V = -F_i$$

$$M = -F_i x$$

$$EI\theta = -\frac{F_i x^2}{2} + C_1$$



$$EIy = -\frac{F_i x^3}{6} + C_1 x + C_2$$

B.C.

$$EIy(x=0) = 0 = C_2$$

$$EIy(x=l_b) = 0 = -\frac{F_i l_b^3}{6} + C_1 l_b \Rightarrow C_1 = \frac{F_i l_b^2}{6}$$

Beam Profile

$$EI\,y(x) = -\frac{F_i x^3}{6} + \frac{F_i l_b^2 x}{6}$$

$$y(x) = -\frac{F_i}{6EI}\left(x^3 - x l_b^2\right) = \boxed{\frac{-M_i/l_b}{6EI}\left(x^3 - x l_b^2\right)}$$

Stiffness

$$K_{eq}(x) = \frac{M_i}{y(x)} = \boxed{\frac{6EI\,l_b}{x l_b^2 - x^3}}$$

stiff w/ F_i input is

$$K_{eq} = \frac{6EI}{x l_b^2 - x^3}$$

Point of least stiffness (greatest deflection)

$$\Theta(x) = 0 = -\frac{\cancel{F_i} x^2}{2} + \frac{\cancel{F_i} l_b^2}{6}$$

$$0 = -3x^2 + l_b^2$$

$$x = \pm\sqrt{\frac{l_b^2}{3}} = \frac{l_b\sqrt{3}}{3} \text{ or } \cancel{-\frac{l_b\sqrt{3}}{3}}$$ not applicable

$$x_{min} = \frac{l_b\sqrt{3}}{3} = \frac{l_b}{\sqrt{3}} = \frac{l_b}{3^{1/2}}$$

Max deflection

$$y_{max} = y(x_{min}) = \frac{-F_i}{6EI}\left(x_{min}^3 - x_{min} l^2\right)$$

$$= \frac{-F_i}{6EI}\left(\frac{l^3}{3^{3/2}} - \frac{l^3}{3^{1/2}}\right)$$

$$= -\frac{F_i l^3}{6\sqrt{3}EI}\left(\frac{1}{3} - 1\right) = \boxed{\frac{F_i l^3}{9\sqrt{3}EI}}$$

Shape function

$$\frac{y(x)}{y_{max}} = \frac{\frac{-\cancel{F_i}}{6\cancel{EI}}(x^3 - x l^2)}{\frac{\cancel{F_i} l^3}{9\sqrt{3}\cancel{EI}}} = -\frac{(x^3 - x l^2)}{\cancel{6}\,2}\,\frac{\cancel{9}^{3}\sqrt{3}}{l^3}$$

$$y(x) = y_{max}\left[\frac{3\sqrt{3}(x l^2 - x^3)}{2 l^3}\right]$$

Finding M_{eff}

$$KE = \frac{1}{2}\int dm\,V^2 = \left[\frac{1}{2}\int_0^{l_b} \gamma\,dx\left(\dot{y}_{max}\,\frac{3\sqrt{3}(x l^2 - x^3)}{2 l^3}\right)^2\right]$$

$$= \frac{27}{8 l^6}\gamma\,\dot{y}_{max}^2 \int_0^{l} (x l^2 - x^3)^2\,dx$$

$$= \frac{27}{8 l^6}\gamma\,\dot{y}_{max}^2 \int_0^{l} x^2 l^4 - 2x^4 l^2 + x^6\,dx$$

$$KE = \frac{27}{8 l_b^6}\, \gamma\, \dot{y}_{max}^2 \left[\frac{x^3 l_b^4}{3} - \frac{2x^5 l_b^2}{5} + \frac{x^7}{7} \right]_{x=0}^{x=l_b}$$

$$= \frac{27}{8 l_b^6}\, \gamma\, \dot{y}_{max}^2 \left(\frac{l_b^7}{3} - \frac{2 l_b^7}{5} + \frac{l_b^7}{7} \right)$$

$$= \frac{27}{8 l_b^6}\, \gamma\, \dot{y}_{max}^2 \left(\frac{35 l_b^7}{105} - \frac{42 l_b^7}{105} + \frac{15 l_b^7}{105} \right)$$

$$= \frac{27}{\cancel{8} \cancel{l_b^6}}\, \gamma\, \dot{y}_{max}^2 \left(\frac{\cancel{8} l^{\cancel{7}}}{105} \right)$$

$$= \frac{\cancel{27}\,9}{\cancel{105}\,35}\, \gamma\, \dot{y}_{max}^2\, l_b \qquad \gamma = \frac{m_b}{l_b}$$

$$= \frac{9 m_b \dot{y}_{max}^2}{35}$$

$$= \underbrace{\frac{18 m_b}{35}}_{m_{eff}} \left(\tfrac{1}{2} \dot{y}_{max}^2 \right)$$

$\frac{rad}{s} \left(\frac{1\,cyc}{2\pi\,rad} \right)$

Finding K_{eff}

$$K_{eff} = K_{eq}(x = x_{min}) = \frac{6EI}{\frac{l_b^3}{3^{1/2}} - \frac{l_b^3}{3^{3/2}}} = \frac{6EI}{\frac{3 l_b^3 - l_b^3}{3^{3/2}}}$$

$$= \frac{18\sqrt{3}\, EI}{2 l_b^3} = \frac{9\sqrt{3}\, EI}{l_b^3}$$

ω_n

$$\omega_n(x = x_{min}) = \sqrt{\frac{K_{eff}}{m_{eff}}} = \sqrt{\frac{\frac{9 m_b}{35}}{\frac{9\sqrt{3}\, EI}{l_b^3}}} = \sqrt{\frac{m_b}{35} \frac{l_b}{\sqrt{3}\, EI}}$$

$$= \boxed{l_b \sqrt{\frac{m_b l_b}{35\sqrt{3}\, EI}}}$$

Using strain energy for K_{eff}

$$y(x) = y_{max}\left[\frac{3\sqrt{3}\,(x\,l^2 - x^3)}{2l^3}\right]$$

$$y'(x) = y_{max}\left[\frac{3\sqrt{3}\,(l^2 - 3x^2)}{2l^3}\right]$$

$$y''(x) = -6y_{max}\left(\frac{3\sqrt{3}}{2l^3}\right)x$$

$$= -\frac{9\sqrt{3}\,y_{max}\,x}{l^3}$$

$$V_{bending} = \frac{1}{2}\int_0^l EI\left(\frac{-9\sqrt{3}\,y_{max}\,x}{l^3}\right)^2 dx$$

$$= \frac{1}{2}EI\left(\frac{243}{l^6}y_{max}^2\right)\int_0^l x^2\,dx$$

$$= \frac{243EI}{2l^6}y_{max}^2\left[\frac{x^3}{3}\right]_0^l$$

$$= \frac{243EI}{6l^3}y_{max}^2$$

$$= \frac{1}{2}\underbrace{\left(\frac{243EI}{3l^3}\right)}\,y_{max}^2$$

$$\therefore\ K_{eff} = \frac{81EI}{l^3}$$

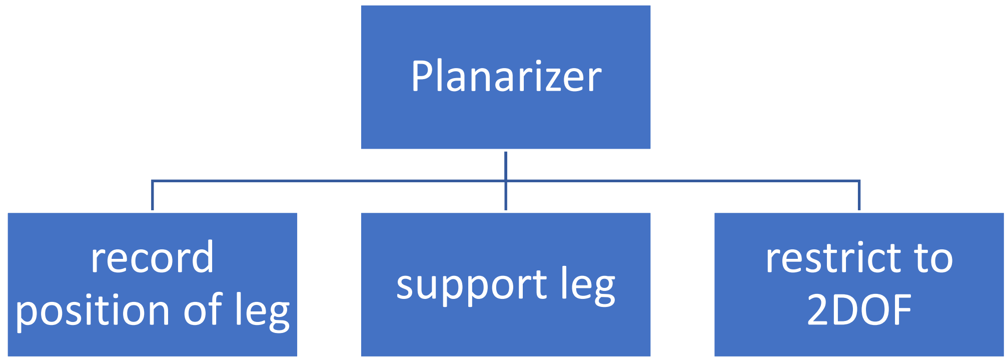
$$\omega_n = \sqrt{\frac{K_{eff}}{M_{eff}}} = \sqrt{\frac{\frac{81EI}{l^3}}{\frac{18m_b}{35}}} = \sqrt{\frac{81EI}{l^3}\,\frac{35}{18m_b}}$$

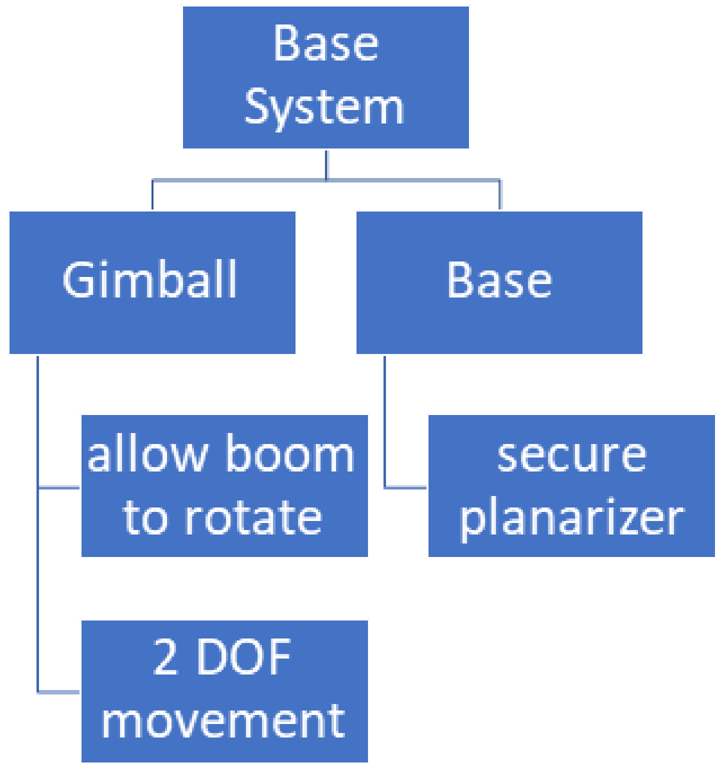
$$= \sqrt{\frac{315EI}{2m_bl^3}}$$

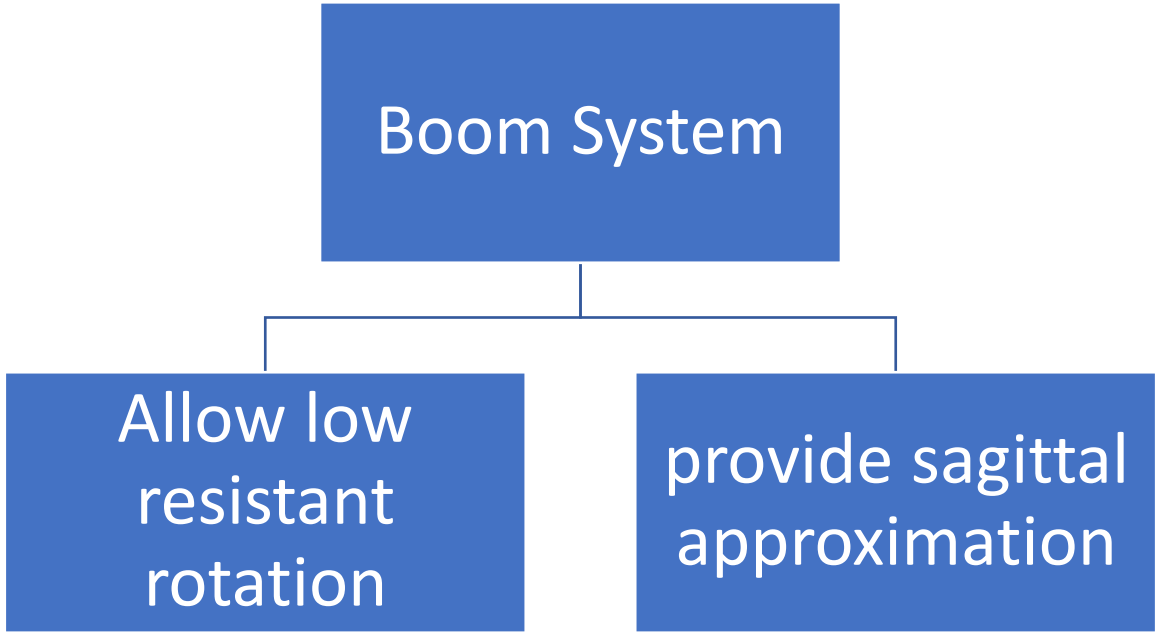
Appendix P: Failure Modes and Analyses (FMEA)

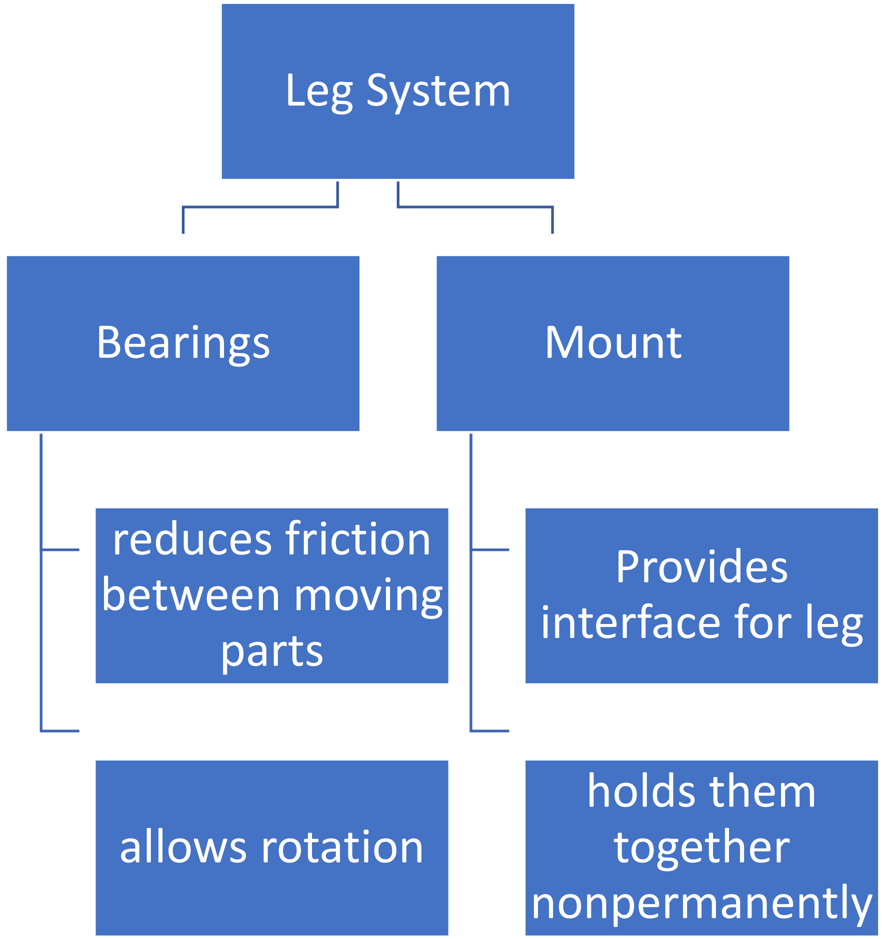
Design Trees

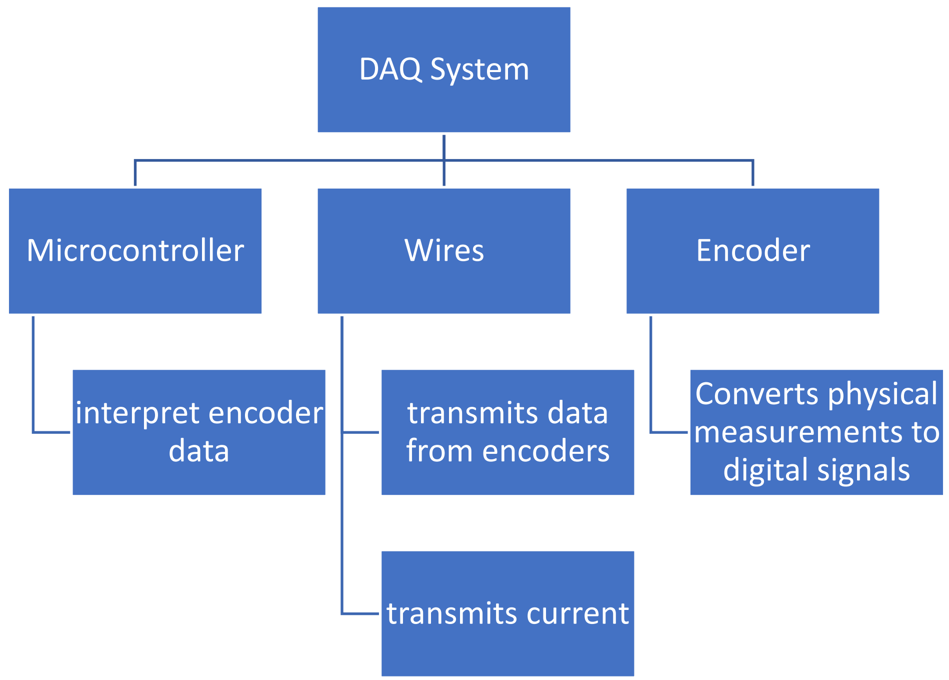
Function Trees



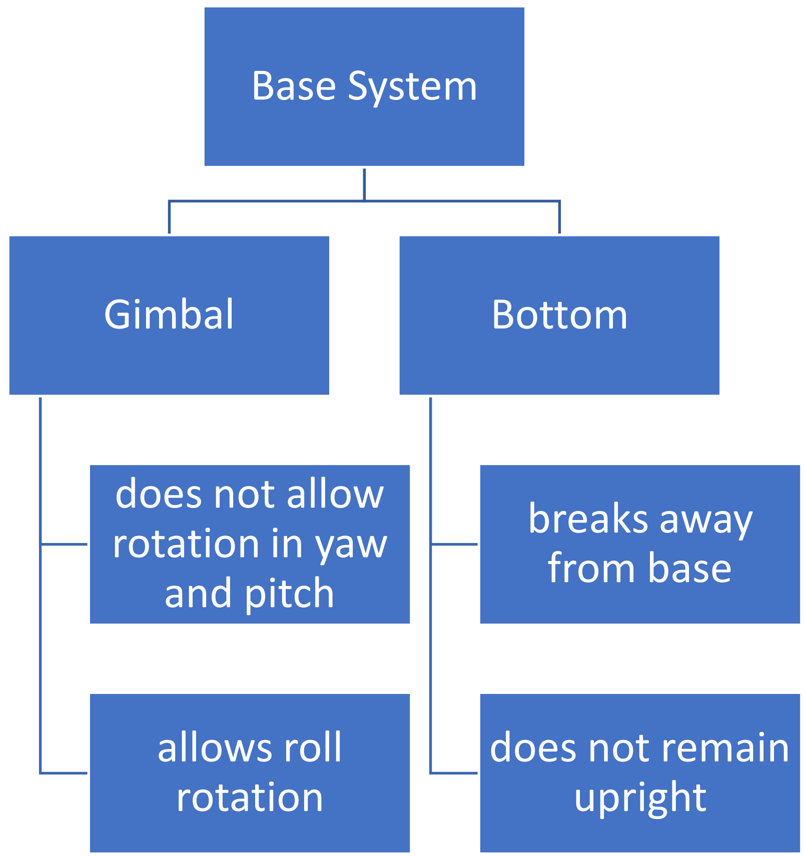

Base System
Gimball
Base
allow boom to rotate
2 DOF movement
secure planarizer

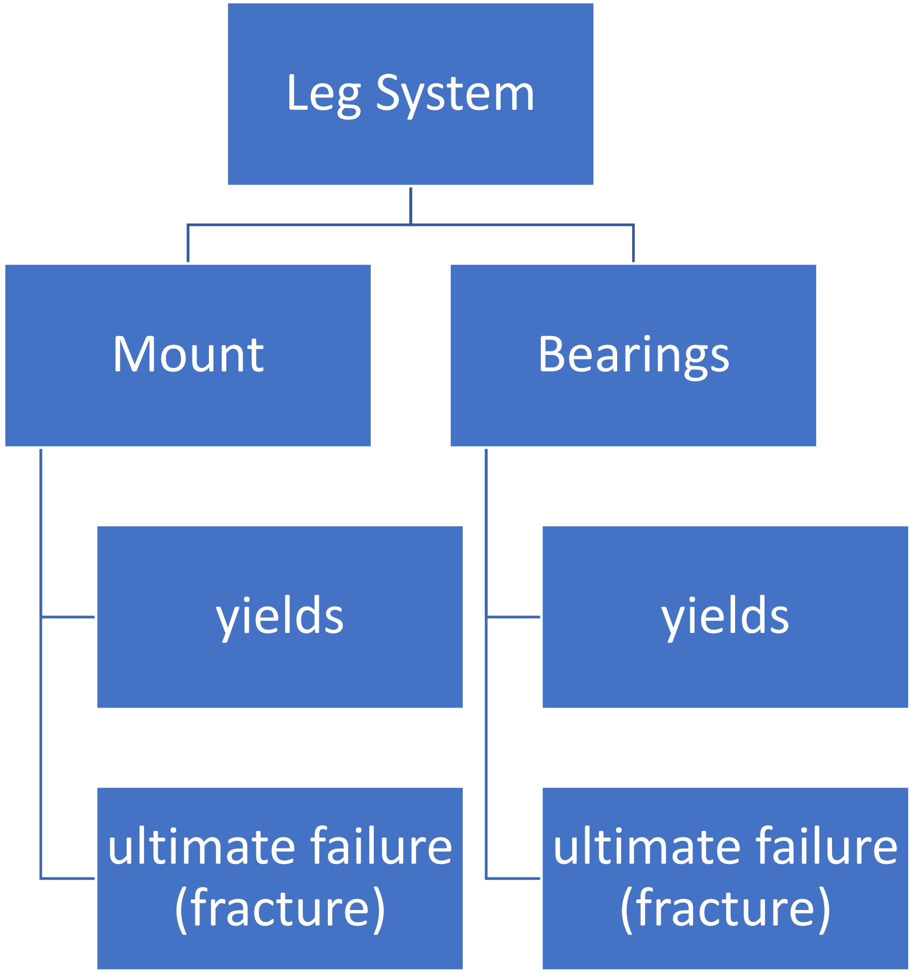

Boom System
Allow low resistant rotation
provide sagittal approximation


Leg System
Bearings
Mount
reduces friction between moving parts
allows rotation
Provides interface for leg
holds them together nonpermanently

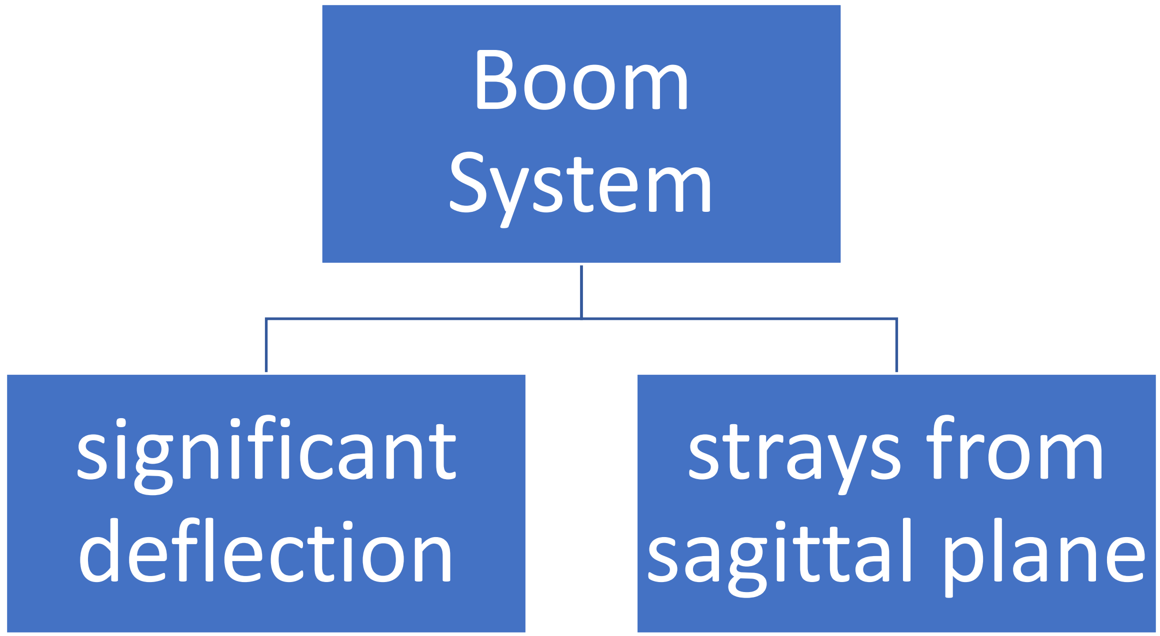

DAQ System
Microcontroller
Wires
Encoder
interpret encoder data
transmits data from encoders
transmits current
Converts physical measurements to digital signals

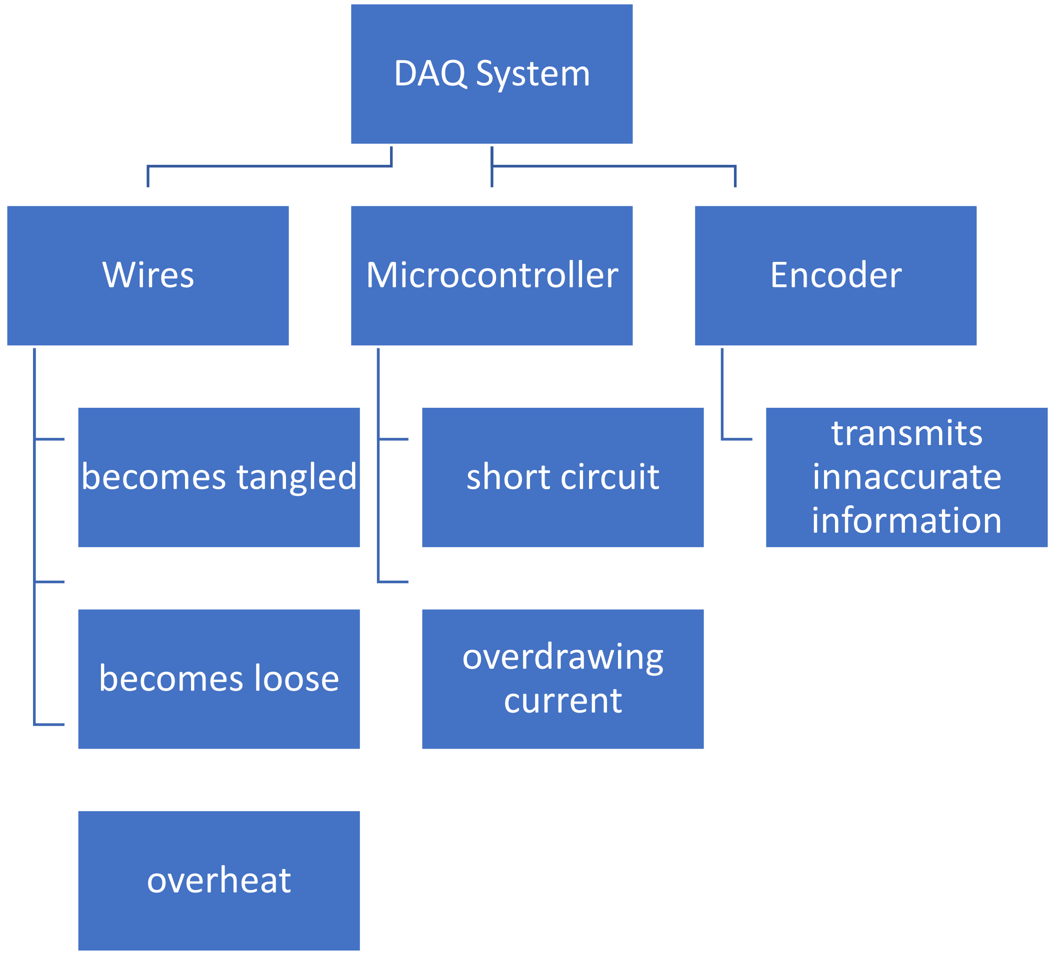
Failure Trees





Leg System
Mount
Bearings
yields
ultimate failure (fracture)
yields
ultimate failure (fracture)


Boom System
significant deflection
strays from sagittal plane


DAQ System
Wires
Microcontroller
Encoder
becomes tangled
short circuit
transmits innaccurate information
becomes loose
overdrawing current
overheat

Appendix Q: Design Verification Plan

DVP&R - Design Verification Plan (& Report)

Project:	Planarizer		Sponsor:	Charlie Refvem, CP Legged Robot Team						Edit Date:	3/7/2022
TEST PLAN										**TEST RESULTS**	
Test #	Specification	Test Description	Measurements	Acceptance Criteria	Required Facilities/Equipment	Parts Needed	Responsibility	TIMING		Numerical Results	Notes on Testing
								Start date	Finish date		
1	1,8	Weigh assembly and swing on a pendulum to determine mass moment of inertia, approximate center of gravity location, and mass	mass, period of swing, mark on planarizer where CG is	within 10% of predicted velocity efficiency	ME lab, scale, Moment of inertia jig	Gimbal Assembly, Booms, Leg Mount	Matthew	2/27/2022	2/27/2022	I_pitch: 0.695 lbf-ft^2 I_yaw: 1.011 lbf-ft^2 eta (yaw): 71.8% eta (pitch): 85.0%	There was a lot of damping innate to our system, so we let the planarizer swing many times and analyzed the response with the most oscillations then averaged those values.
2	2, 6	Twist encoder to verify values and check on streaming functionality. Make note of any latency issues Determine bluetooth latency.	Bluetooth response time, module to module distance, streaming latency, polling rate	200 Hz or higher, streaming latency is less than 100 ms	ME lab	encoder, microcontroller	Aaron	3/12/2022	3/12/2022	Streaming Latency: 90 ms Bluetooth response time: 6.9 ms Polling Rate: 60 Hz	The bluetooth response time was calculated using just two data points, so it may not be the most accurate. The streaming latency is based off of expecting a 60Hz polling rate and refreshing the plot every 6 data points. The polling rate is difficult to get higher than it currently is.
3	5	Statically load boom based off 27 lb ground reaction force (applied moment changes based off of length of boom). Check for largest point of deflection. Note down any effects that may interfere with position calculations.	vertical boom deflection	1 mm or less	ME lab	Booms	Tim	2/14/2022	2/14/2022	15 lb: 0.4855 in 20 lb: 0.6085 in 35 lb: 1.0475 in	Ensure that there are three tables at your disposal. Attach the boom to two rollers on the two end tables. On the middle table, place the height gauge. Use a rope to attach the dumbbells to the boom. Lower the height gauge until it contacts the center of the boom's surface. Go up to 35 lb max, but can use intermediary weights if desired. Calculate the uncertainty percentage due to deflection based on the Data Resolution uncertainty propagation calculations.

4	7	Assemble planarizer and record time, verify that it can be easily assembled in a timely manner. Make note of anything that is difficult or awkward to do.	time it takes to assemble planarizer, notes on difficulty	20 minutes or less	ME lab	full assembly	Eric	3/3/2022	3/3/2022	Total Time: 39 min 40 s	**LEG MOUNT:** Put on pillow bearings: 4.98 min, Join leg plates: 7.38 min **BASE ASSEMBLY:** Base plate onto plywood: 2.72 min, Bottom encoder install: 9.42 min **BOOM ASSEMBLY:** Boom Assembly to Leg Mount: 2 min, Boom Assembly to Yoke: 3 min **GIMBAL ASSEMBLY:** Yoke Assembly with Shaft Collars, Shims: 2.5 min, Top Encoder Installation: 3.5 min **DAQ MOUNT ASSEMBLY:** DAQ Mount to Gimbal Assembly: 4.2 min

Appendix R: Indented Bill of Materials

Planarizer

Indented Bill of Material (iBOM)

Assy Level	Part Number	Descriptive Part Name					Qty	Material Cost	S/H/Tax Cost	Production Cost	Total Cost	Part Source	More Info
		Lvl0	*Lvl1*	*Lvl2*	*Lvl3*	*Lvl4*							
0	0	**Final Assy**									------		
1	00_01		**Base Assy**								------		
2	00_01_01			Base Plate White Oak Plywood			1	$ 16.75	$ 1.47	$ -	$ 18.22	Home Depot	https://www.homedepot.com/
2	00_01_02			Base Flange			1	$ 16.00	$ -	$ -	$ 16.00	Ebay	Weldbend A105 Carbon Steel F
2	00_01_03	COTS		.266 ID, .875 OD Washers			4	$ 0.09			$ 0.37	McMaster-Carr	Pack of 50 sold, Cost based on
2	00_01_04	COTS		1/4"-20 Thread, 1-1/8" Long Pan Head Phillips Screw			4	$ 2.80			$ 11.19	McMaster-Carr	Pack of 25 sold, based on indi
2	00_01_05	COTS		1/4-20" Hex Nut			6	$ 0.06			$ 0.33	McMaster-Carr	Pack of 100 sold, based on inc
2	00_01_06			Fixed Housing			1	$ 48.04			$ 48.04	OnlineMetals	3" OD Round Stock, 6.5" Length
2	00_01_07			Base Shaft			1	$ 13.21			$ 13.21	OnlineMetals	1.25" OD Round, 12" Length
2	00_01_08	COTS		R16-ZZ Ball Bearings			2	$ 6.15			$ 12.30	Ebay	https://www.ebay.com/itm/14
2	00_01_09	COTS		Retaining Ring			1	$ 0.23			$ 0.23	McMaster-Carr	Pack of 50 sold, Cost based on
2	00_01_10			Encoder Plate			1	$ 9.79			$ 9.79	OnlineMetals	0.25"x3"x12"
2	00_01_11			Encoder Plate and Cover Plate Screws			8	$ 0.08			$ 0.61	McMaster-Carr	Pack of 100 sold, based on inc
2	00_01_12			Cover Plate			1				$ -		Same stock as encoder plate
2	00_01_13			Base Adapter			1				$ -		Same stock as base shaft
2	00_01_14	COTS		5/16" Shoulder Bolts			2	$ 4.06			$ 8.12	McMaster-Carr	
2	00_01_15	COTS		1/2" Bore Slip Ring			1	$ 35.94			$ 35.94	Ebay	NEW 6Wires 380V AC/DC 10A
2	00_01_16	COTS		1/2" Bore Encoder			1	$ 127.84			$ 127.84	US Digital	E6 | US Digital
1	00_02		**Gimbal Assy**								$ -		
2	00_02_01			Clevis Yoke			1	$ 38.70	$ -	$ -	$ 38.70	etal.com/aluminu	
2	00_02_02	COTS		Carbon Steel Ring Shims			4	$ 0.63			$ 2.52	McMaster-Carr	Pack of 10 sold, based on indi
2	00_02_03	COTS		Clevis Pins			2	$ 2.54	$ -	$ -	$ 5.09	McMaster-Carr	Pack of 5 sold, based on indivi
2	00_02_04	COTS		0.5" Pin Locking Shaft Collars			4	$ 4.91			$ 19.64	on.com/Climax-2C-	
2	00_02_05	COTS		1/2" Bore Encoder			1	$ 127.84			$ 127.84	US Digital	E6 | US Digital
											$ -		
1	00_03		**Boom Assy**								$ -		
2	00_03_01	COTS		0.5" OD Boom			2	$ 29.90	$ -	$ -	$ 59.80	e.com/Roll-	
2	00_03_02			Boom Shaft Ends			2	$ 50.61	$ -	$ -	$ 101.22	aster.com/3463N5	
2	00_03_03	COTS		Boom Set Screw			1	$ 0.28			$ 0.28	McMaster-Carr	Sold in packs of 25, only one u
											$ -		

1	00_04		**Leg Mount Assy**									$ -			
2	00_04_01			CAN Side Mount				1	$ -			$ -		3D Printed	
2	00_04_02			Main Leg Mount				1	$ -			$ -		3D Printed	
2	00_04_03			Left Spacer				1	$ -			$ -		3D Printed	
2	00_04_04			Right Spacer				1	$ -			$ -		3D Printed	
2	00_04_05	COTS		Lock Nuts				2	$ 0.05			$ 0.11			
2	00_04_06			Carbon Fiber Tube Multi-Angle Connector				4	$ 3.25			$ 13.00		https://dragonplate.com/05-Carbon-Fiber-Tube-C	
2	00_04_07	COTS		Mounted Shielded Steel Ball Bearing				4	$ 17.04			$ 68.16		aba.com/shop/agi	
2	00_04_08	COTS		1/4" Bolts				2	$ 0.11			$ 0.22		McMaster-Carr	Sold in packs of 100, only one
2	00_04_09	COTS		#5-40 Bolts				8	$ 0.01			$ 0.05		Grainger	Sold in packs of 50, based on
2	00_04_10	COTS		#5-40 Nuts				8	$ 0.08			$ 0.63		Grainger	Sold in packs of 50, based on
1	00_05		**DAQ Mount Assy**												
2	00_05_01			DAQ Mount Plate				1	$ -			$ -		3D Printed	
2	00_05_02			DAQ Mount Bolts				5	$ 0.01			$ 0.05		Grainger	Same as Leg Mount
2	00_05_03			DAQ Mount Nuts				5	$ 0.08			$ 0.40		Grainger	Same as Leg Mount
2	00_05_04			Power Bank				1	$ 15.28	$ 1.34		$ 16.62		Amazon	Anker Charger (10000 mAh)
2	00_05_05			STM32 L476RG Microcontroller				1	$ -	$ -	$ -	$ -		er.com/ProductDe	
												$ -			
	Total Parts											**$ 738.28**			

Subassembly	Raw Material / Equipment	Quantity	Cost ($)
Base Assy	Base Plate White Oak Plywood	1	$ 18.22
	Base Flange	1	$ 16.00
	.266 ID, .875 OD Washers	4	$ 0.37
	1/4"-20 Thread, 1-1/8" Long Pan Head Phillips Scre	4	$ 11.19
	1/4-20" Hex Nut	8	$ 0.44
	Fixed Housing	1	$ 48.04
	Base Shaft	1	$ 13.21
	R16-ZZ Ball Bearings	2	$ 12.30
	Retaining Ring	1	$ 0.23
	Encoder Plate	1	$ 9.79
	Encoder Plate and Cover Plate Screws	8	$ 0.61
	Cover Plate	1	$ -
	Base Adapter	1	$ -
	5/16" Shoulder Bolts	2	$ 8.12
	1/2" Bore Slip Ring	1	$ 35.94
	1/2" Bore Encoder	1	$ 127.84
Gimbal Assembly	Clevis Yoke	1	$ 38.70
	Carbon Steel Ring Shims	4	$ 2.52
	Clevis Pins	2	$ 5.09
	0.5" Pin Locking Shaft Collars	4	$ 19.64
	1/2" Bore Encoder	1	$ 127.84
Boom Assembly	0.5" OD Boom	2	$ 59.80
	Boom Shaft Ends	2	$ 101.22
	Boom Set Screw	1	$ 0.28
Leg Mount Assembly	CAN Side Mount	1	$ -
	Main Leg Mount	1	$ -
	Left Spacer	1	$ -
	Right Spacer	1	$ -
	Lock Nuts	2	$ 0.11
	Carbon Fiber Tube Multi-Angle Connector	4	$ 13.00
	Mounted Shielded Steel Ball Bearing	4	$ 68.16
	1/4" Bolts	2	$ 0.22
	#5-40 Bolts	8	$ 0.05
	#5-40 Nuts	8	$ 0.63
DAQ Mount Assembl	DAQ Mount Plate	1	$ -
	DAQ Mount Bolts	5	$ 0.05
	DAQ Mount Nuts	5	$ 0.40
	Power Bank	1	$ 16.62
	STM32 L476RG Microcontroller	1	$ -
Total		**$757**	

Appendix S: Project Budget

Part	Vendor's Part #	Material Cost	S&H Costs	Tax	Qty	Total Cost	Vendor	Assembly Part #	Lead Time	How Purchased	Date Purchased	Notes
1"x2' PVC PIPE	SKU #1003272478	$ 2.61	$ -		1	$ 2.61	Home Depot		Instant	In-Store	10/17/2021	
4"x4" HEADER HANGER	SKU #1000076141	$ 6.68	$ -		2	$ 13.36	Home Depot		Instant	In-Store	10/17/2021	
3/8"X48" DOWEL	SKU #216107	$ 1.03	$ -		1	$ 1.03	Home Depot		Instant	In-Store	10/17/2021	
3/4" PVC MALE ADAPTER	SKU #188131	$ 0.51	$ -		2	$ 1.02	Home Depot		Instant	In-Store	10/17/2021	
1" PVC MALE ADAPTER	SKU #188158	$ 0.87	$ -		1	$ 0.87	Home Depot		Instant	In-Store	10/17/2021	
1"X3/4" PVC FEMALE ADAPTER	SKU #535578	$ 1.61	$ -		1	$ 1.61	Home Depot		Instant	In-Store	10/17/2021	
1" BLK FLOOR FLANGE	SKU #860727	$ 9.84	$ -		1	$ 9.84	Home Depot		Instant	In-Store	10/17/2021	
3/4" BLK FLOOR FLANGE	SKU #1002654604	$ 8.38	$ -		1	$ 8.38	Home Depot		Instant	In-Store	10/17/2021	
MCH SCREW ZNC COMBO #8X3/4	SKU #185130	$ 1.28	$ -		1	$ 1.28	Home Depot		Instant	In-Store	10/17/2021	
3/4" X 2' PVC PIPE	SKU #254518	$ 1.96	$ -		1	$ 1.96	Home Depot		Instant	In-Store	10/17/2021	
1/2" X 10' PVC40 PE PIPE	SKU #193682	$ 3.61	$ -		1	$ 3.61	Home Depot		Instant	In-Store	10/17/2021	
1/4" NUT AND WASHER KIT	SKU #595397	$ 2.56	$ -		1	$ 2.56	Home Depot	1150	Instant	In-Store		WHAT WAS THIS FOR?
3/8"-24C NUT AND BOLT	SKU #661872	$ 1.26	$ -		1	$ 1.26	Home Depot	1220	Instant	In-Store		WHAT WAS THIS FOR?
1/8" NUT, BOLT, WASHER KIT	Model# 815841	$ 1.40	$ -		4	$ 5.60	Home Depot	1330	Instant	In-Store		WHAT WAS THIS FOR?
8" STEEL CIRCULAR PLATE	SC1-8	$ 38.50	$ 14.11		1	$ 52.61	Metals Depot	1100	1 WEEK	Online		
MACHINABLE SHAFT ENDS	3463N51	$ 46.11	$ -		2	$ 92.22	McMaster-Carr	1320	2 days	Online		
E6 BASE ENCODER	E6-10000-1000-IE-D-H-D-3	$ 123.79			1	$ 123.79	US Digital	1510	1 WEEK	Online		
Slip Ring	ROB-13064	$ 14.95	$ 13.91	$ 2.09	1	$ 30.95	Sparkfun Electronics	1550	1 WEEK	Online		
1004-1005 Carbon Steel Clevis Pin with Hairpin Cotter Pin, 1/2" Diamter, 3-3/4" Usable Length, Packs	98306A643	$ 12.72	$ 9.06	$ 0.92	1	$ 22.70	McMaster-Carr	NA	1 day	Online	2/2/2022	**Purchased with Personal Acct**
316 Stainless Steel Easy-to-Install Thread Locking Insert, 4-40 Thread Size	90266A339	$ 6.73	$ 8.60	$ 2.35	3	$ 31.14	McMaster-Carr	NA	1 day	Online	2/3/2022	**Purchased with Personal Acct**
TiN-Coated Carbide Drill Bit, 43 Gauge Size, 2" Overall Length	8825A471	$ 12.16	$ -	$ -	1	$ 12.16	McMaster-Carr	NA	1 day	Online	2/3/2022	**Purchased with Personal Acct**

	Structural Prototype
	Post-CDR Prototype
	Final Prototype

E6 GIMBAL ENCODER	E6-10000-500-IE-D-H-D	$ 119.79	$ 12.00		1	$ 131.79	US Digital	1520	1 WEEK	Online		
STM32 L476RG MICROCONTROLLER	NUCLEO-L476RG	$ -	$ -		1	$ -	Mouser Electronics	1530	1 WEEK	Sponsor		
Alloy Steel Shoulder Screw, 5/16" Sh Di., 7/8" Sh Lg	91259A582	$ 4.06	$ 8.56	$ 1.18	4	$ 25.98	McMaster-Carr	1220	2 days	Online		
LEG MOUNT PRINTING		$ -	$ -		1	$ -	Aaron's Friend	1430	1 WEEK	In-Person		
LOW PROFILE MOUNTED SHIELDED STEEL BALL	8600N3	$ 17.04			4	$ 68.16	McMaster-Carr	1420	2 days	Online		
0.5" CARBON FIBER TUBE MULTI ANGLE CONNEC	SKU:FDPCK-.5-DIAG-SI	$ 3.25			4	$ 13.00	DragonPlate		1 WEEK	Online		
0.5" OD CARBON FIBER BOOM	SKU #FDPT.500".400"48	$ 29.90	$ 49.44		3	$ 139.14	DragonPlate	1310	1 WEEK	Online		
YOKE RECTANGULAR STOCK	15213	$ 56.88	$8	$4	1	$ 68.99	OnlineMetals	1240	1 WEEK	Online		
0.5" PIN LOCKING SHAFT COLLARS	2C-050	$ 4.91			4	$ 19.64	Amazon	1210	1 WEEK	Online		
Climax Metal 2C-050 Steel Two-Piece Clamping Collar, Black Oxide Plating, 1/2" Bore Size, 1-1/8" OD, With 8-32 x 1/2 Set Screw	2C-050	$ 4.48	$ -	$ 0.91	1	$ 5.39	Amazon	NA	2 days	Online	2/1/2022	**Purchased with I**
Carbon Steel Clevis Pin	98306A643	$ 12.72	$ 9.06	$ 0.92	1	$ 22.70	McMaster-Carr		2 days	Online	2/2/2022	**Purchased with I**
Cylindrical, Socket Head Cap Screw, #5-40, Stainless Steel, 18-8, Plain, 3/4 in Length, PK 50	6XA53	$ 0.29	$ 10.98	$ 0.37	1	$ 11.64	Grainger	NA	4 days	Online	2/9/2022	**Purchased with I**
#5-40 Nylon Insert Lock Nut, Plain Finish, 18-8 Stainless Steel, Right Hand, PK-50	22RV92	$ 3.92	$ -	$ -	1	$ 3.92	Grainger	NA	4 days	Online	2/9/2022	**Purchased with I**
Anker Portable Charger, 313 Power Bank (PowerCore Slim 10K) 10000mAh		$ 15.28	$ -	$ 1.34	1	$ 16.62	Amazon	NA	4 days	Online	2/9/2022	**Purchased with I**
HiLetgo HC-05 Wireless Bluetooth RF Transceiver		$ 8.59	$ -	$ 1.50	2	$ 18.68	Amazon	NA	4 days	Online	2/9/2022	**Purchased with I**
Monoprice 3-Feet USB A to mini-B 5pin 28/28AWG Cable		$ 1.49	$ -	$ 0.26	2	$ 3.24	Amazon	NA	4 days	Online	2/9/2022	**Purchased with I**
HUBDISK-2 2 inch transmissive rotary disk, 10000 CPR, 1/2 inch bore, IE	HUBDISK-2-10000-500-IE	$ 35.26	$ 12.95	$ 2.56	1	$ 50.77	US Digital	NA	1 WEEK	Online	2/10/2022	
1/4 in. x 1-1/4 in. External Hex Hex-Head Cap Screw (10-Pack)	Model #2419	$ 4.15	$ -	$ 0.47	1	$ 4.62	Home Depot	NA	1 WEEK	Online	2/10/2022	**Purchased with I**
#4-40 x 1/4 in. Combo Round Head Zinc Plated Machine Screw (10-Pack)	Store SKU #516511	$ 1.28	$ -	$ -	1	$ 1.28	Home Depot	NA	1 WEEK	Online	2/10/2022	**Purchased with I**
Columbia Forest Products 3/4 in. x 2 ft. x 2 ft. PureBond White Oak Plywood Project Panel (Free Custom Cut Available) 2885 - The Home Depot		$ 16.75		$ 1.47	1	$ 18.22	Home Depot	NA	2/23/2022	Online	2/15/2022	**Purchased with I**
1008-1010 Carbon Steel Ring Shims, 1/8" Thick, 1/2"	3088A512	$ 6.30	$ 8.62	$ 1.30	1	$ 16.22	McMaster-Carr	NA	2 days	Online	2/15/2022	**Purchased with I**
Super-Corrosion-Resistant Cup-Point Set Screw 316 Stainless Steel, 5/16"-18 Thread, 3/8" Long	92313A576	$ 6.96	$ -	$ -	1	$ 6.96	McMaster-Carr	NA	2 days	Online	2/16/2022	**Purchased with I**
Zinc-Plated Steel Oversized Washer for 1/4" Screw Size, 0.266" ID, 0.875" OD Pack of 50	91090A107	$ 4.65	$ -	$ -	1	$ 4.65	McMaster-Carr	NA	2 days	Online	2/17/2022	**Purchased with I**
HiLetgo 2pcs UNO R3 Proto Shield Prototype Expansion Board with SYB-170 Mini Breadboard Based for Arduino UNO R3 ProtoShield		$ 7.19		$ 1.26	2	$ 15.64	Amazon	NA	2 days	Online	2/24/2022	**Purchased with I**
EVISWIY PL2303TA USB to TTL Serial Cable Debug Console Cable for Raspberry Pi 3 Pack		$ 11.99		$ 1.05	1	$ 13.04	Amazon	NA	3 days	Online	2/28/2022	**Purchased with I**
High-Strength Grade 8 Steel Hex Head Screw, Zinc-Aluminum Coated, 1/4"-20 Thread Size, 2"	91286A121	$ 9.00	$ 8.72	$ 0.65	1	$ 18.37	McMaster-Carr	NA	1 Day	Online	3/7/2022	**Purchased with I**
					TOTAL	$ 1,119.22						
					REMAININ	$ (119.22)						
					BUDGET	$ 1,000.00						

Appendix T: FDR Report Edit Log

Report Edit Log

Team: Planarizer

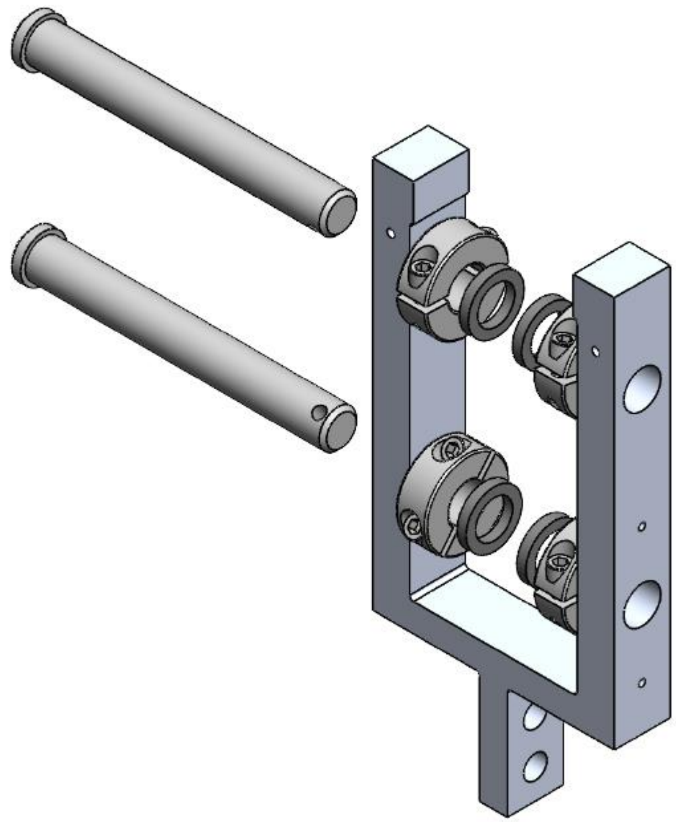
Edits for Report: (Check box)		
	PDR	
	CDR	
	FDR	✓

<u>Be sure to address ALL comments provided by your sponsor and advisor!</u>

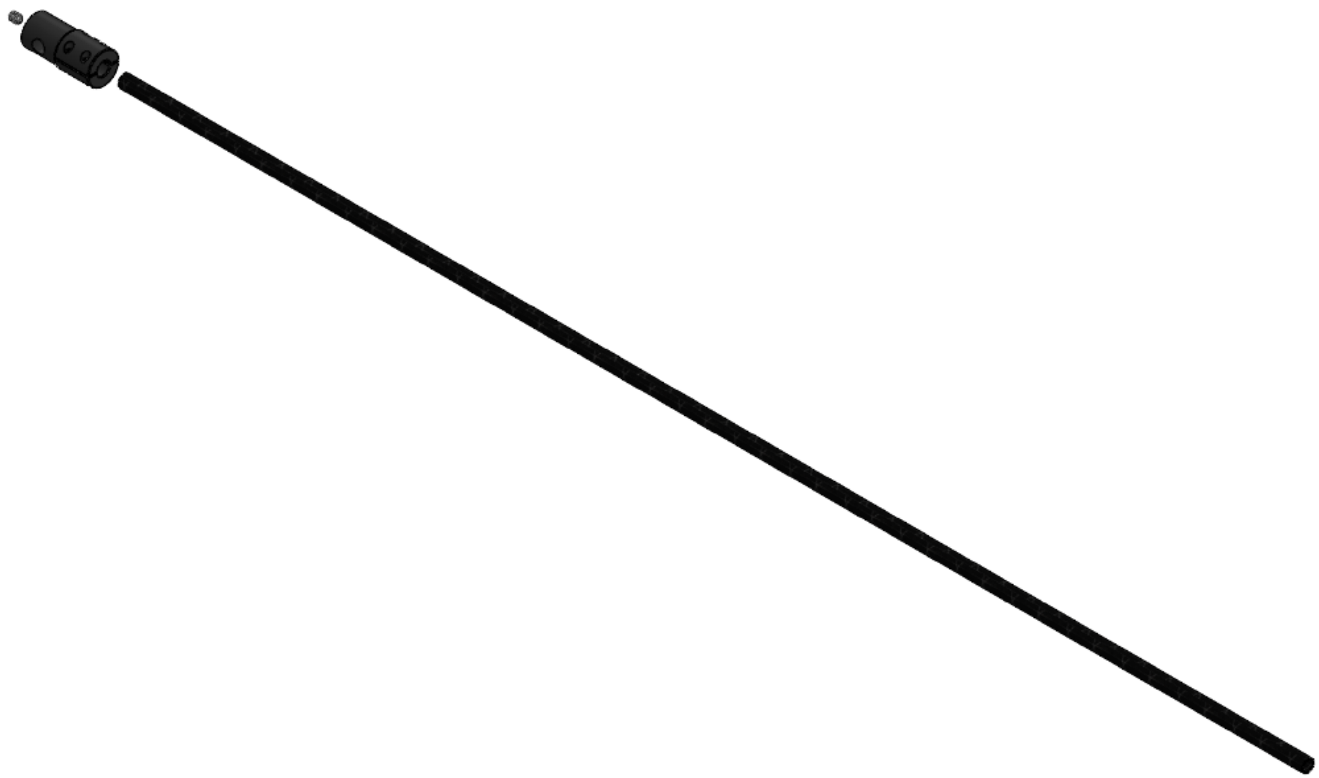
Report Section #	Source of recommended edit (Sponsor, Advisor, Team, Reviewer)	Brief description of edit
1	team	Updated intro with briefs of CDR sections
3.2	sponsor	Modified need of making planarizer portable
3.5	sponsor	Updated target leg speed to 1.3 m/s
Table of Contents	team	Updated figure and heading caption references
Appendix P	advisor	Updated design tree with most recent assembly of components
Appendix I	advisor	Updated Gantt Chart
2.1.1	sponsor	Changed leg mass from 2.5 kg to 1.25 kg
3.2	sponsor	Changed data upload time from 60 seconds to real time
3.2	sponsor	Removed catch mechanism requirement
3.5.8	sponsor	Updated data upload requirement to real time
Table 4.	Team	Updated table title to clarify that these were the specifications coming into PDR

Appendix U: Drawing Package (See Appendix R for iBOM)

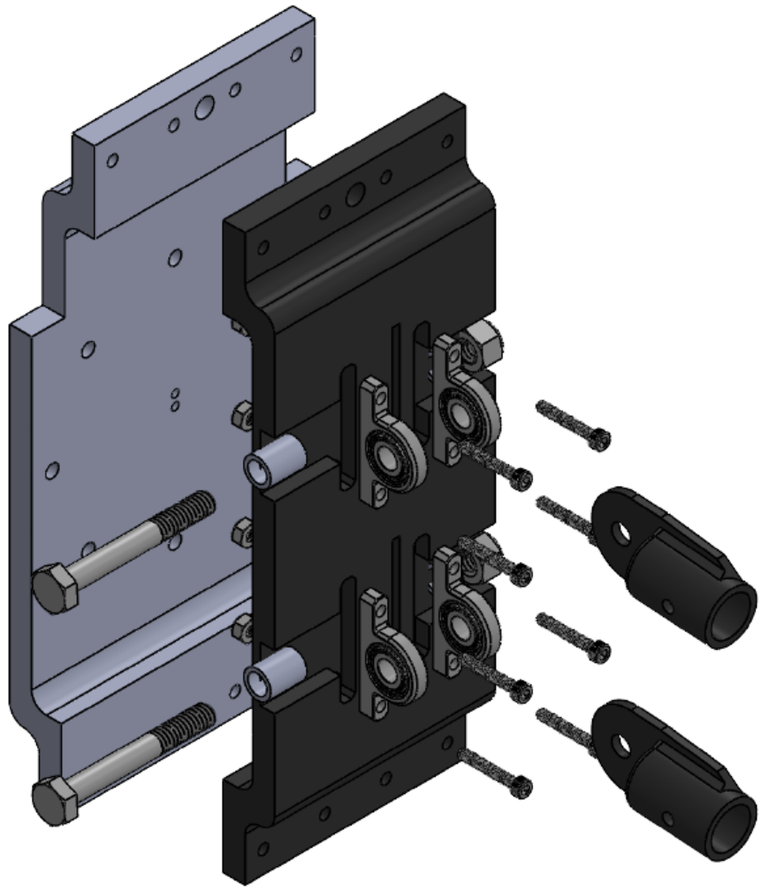
Planarizer	Lab Section:	PART #00_01	Title: BASE ASSEMBLY		Drwn. By: TIM JAIN
Senior Design Project	Dwg. #:	Nxt Asb:	Date: 03/18/22	Scale: 1:4	Chkd. By:



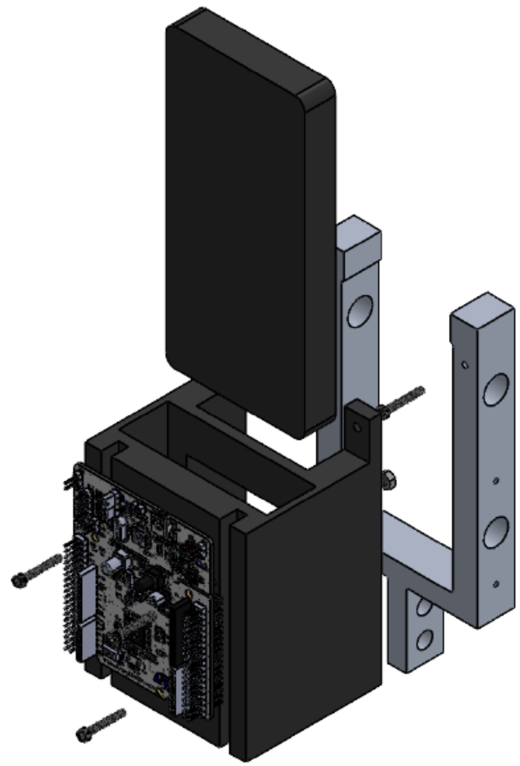
Planarizer Senior Design Project	Lab Section:	PART #	Title: GIMBAL ASSEMBLY		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/18/22	Scale: 1:1	Chkd. By:



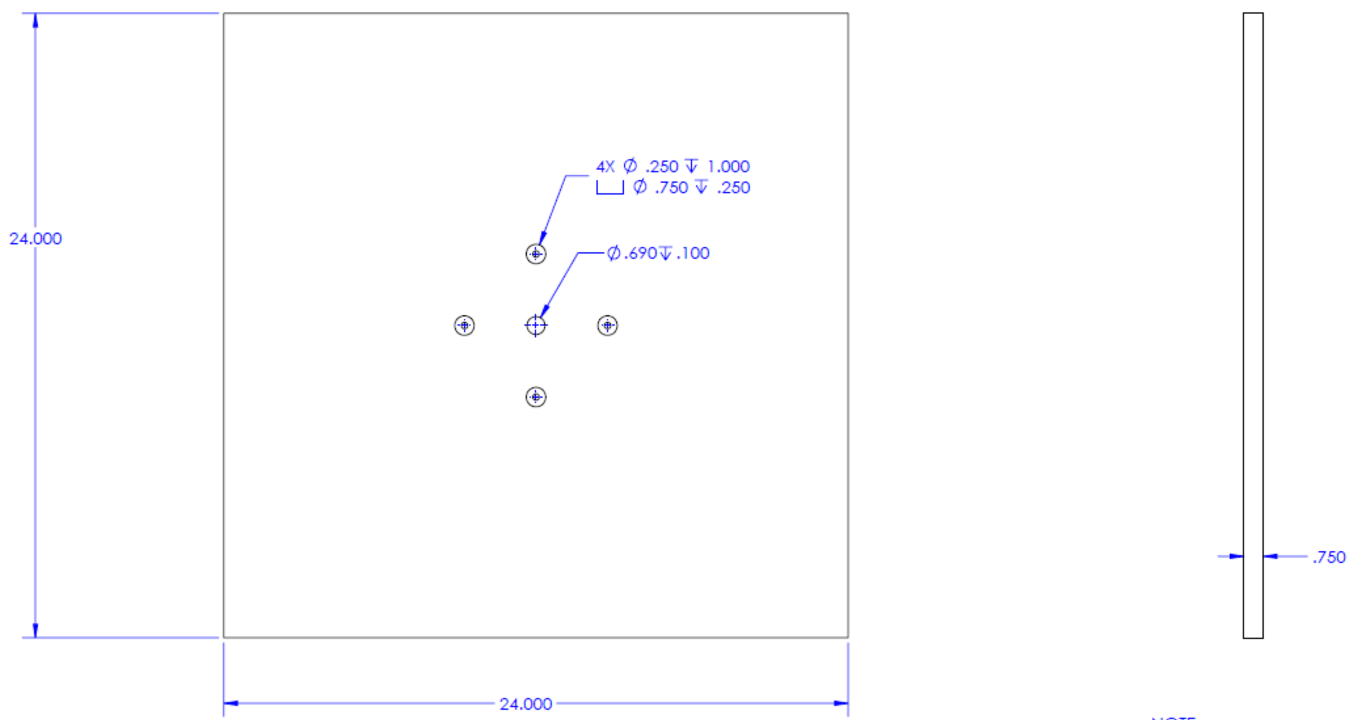
Planarizer Senior Design Project	Lab Section:	PART #	Title: BOOM ASSEMBLY		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/18/22	Scale: 1:3	Chkd. By:



Planarizer Senior Design Project	Lab Section:	PART #	Title: LEG MOUNT ASSEMBLY		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/18/22	Scale: 1:1	Chkd. By:

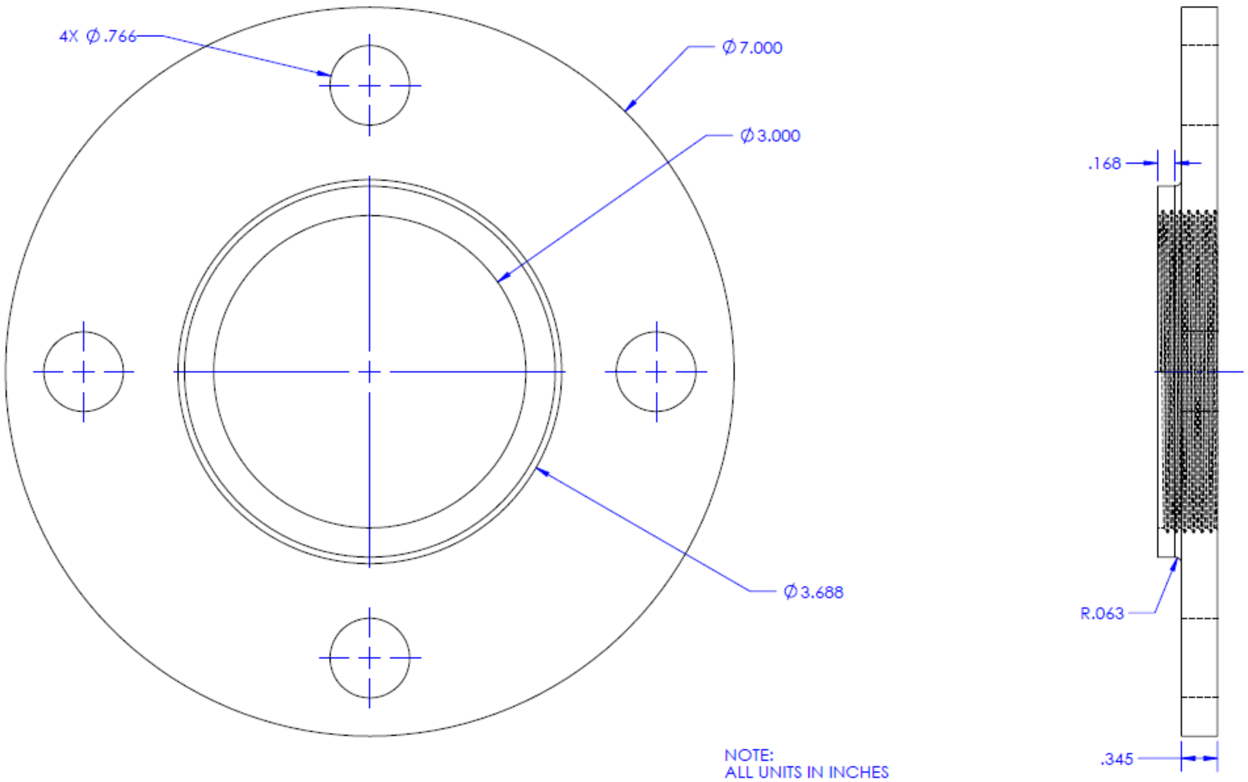


Planarizer Senior Design Project	Lab Section:	PART #	Title: DAQ MOUNT ASSEMBLY		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/18/22	Scale: 1:1.5	Chkd. By:



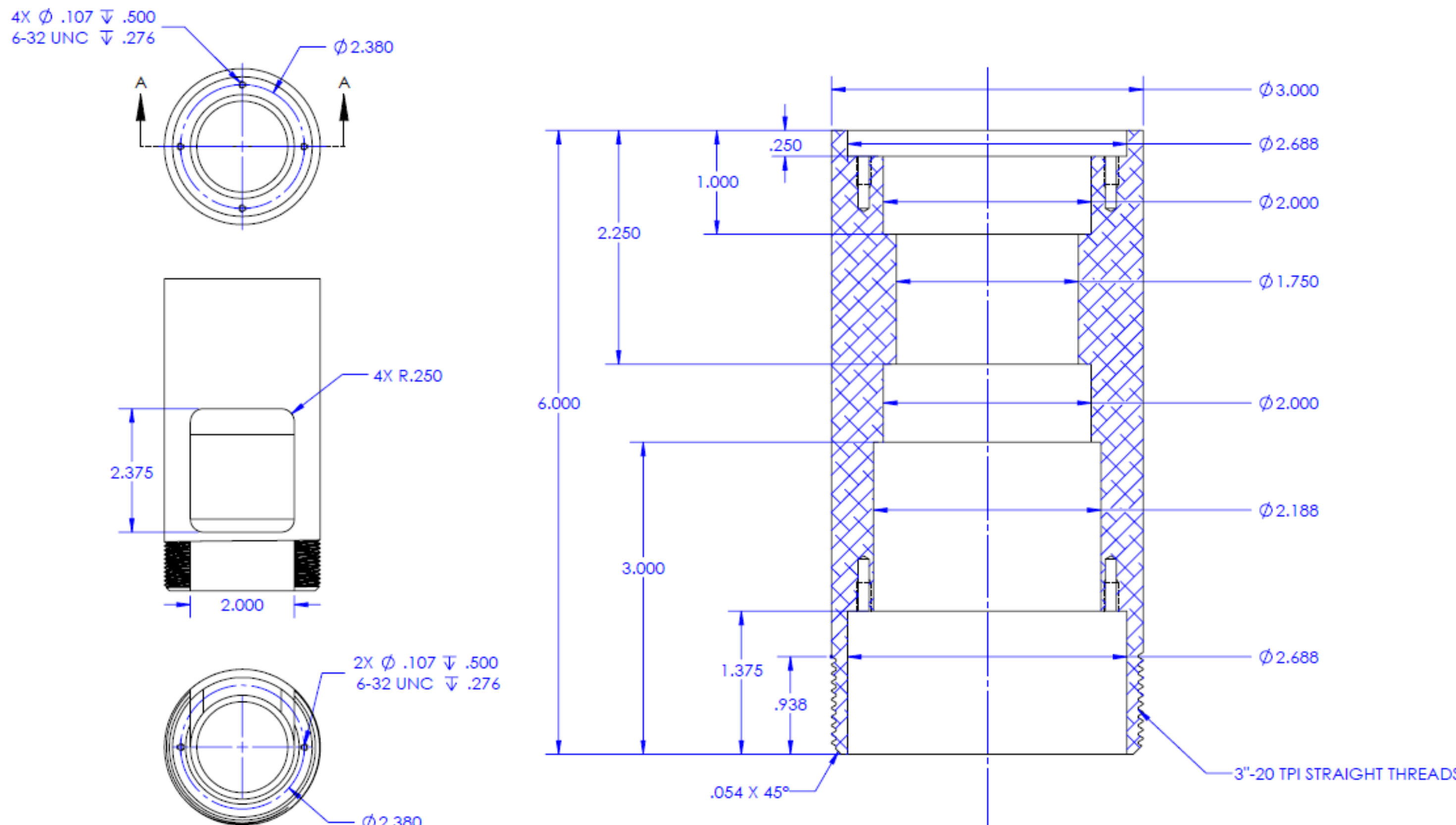
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: WHITE OAK

Planarizer Senior Design Project	Lab Section:	PART #1110	Title: BASE PLATE		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/09/22	Scale: 1:4	Chkd. By:



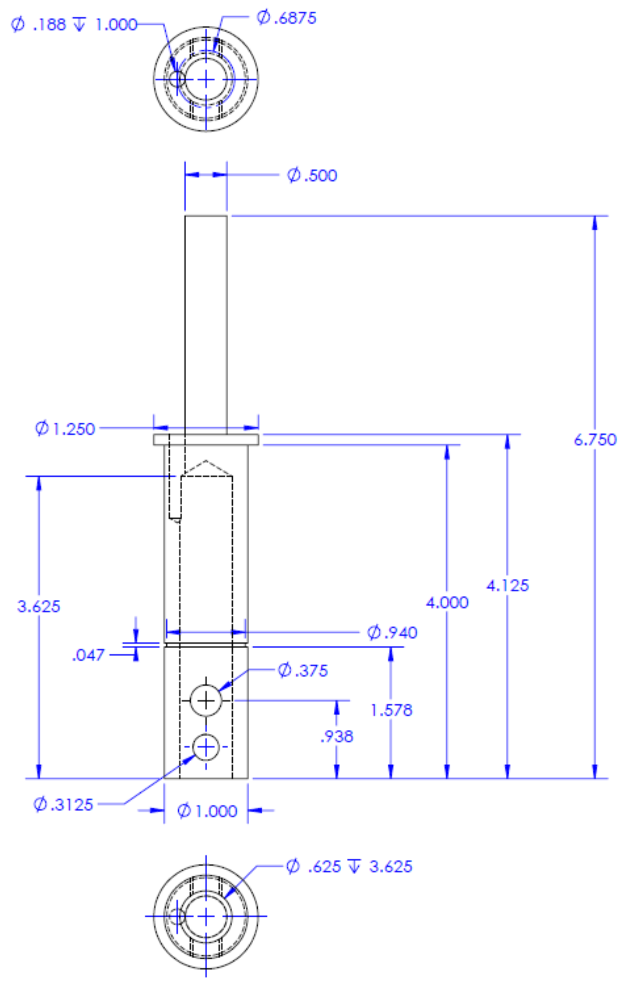
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: A105 CARBON STEEL
IF EBAY PART PURCHASED, SIMPLY REDUCE HEIGHT OF
∅3.688 PORTION TO .168

Planarizer Senior Design Project	Lab Section:	PART #1120	Title: BASE FLANGE		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/10/22	Scale: 1:2	Chkd. By:



NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: 6061 ALUMINUM

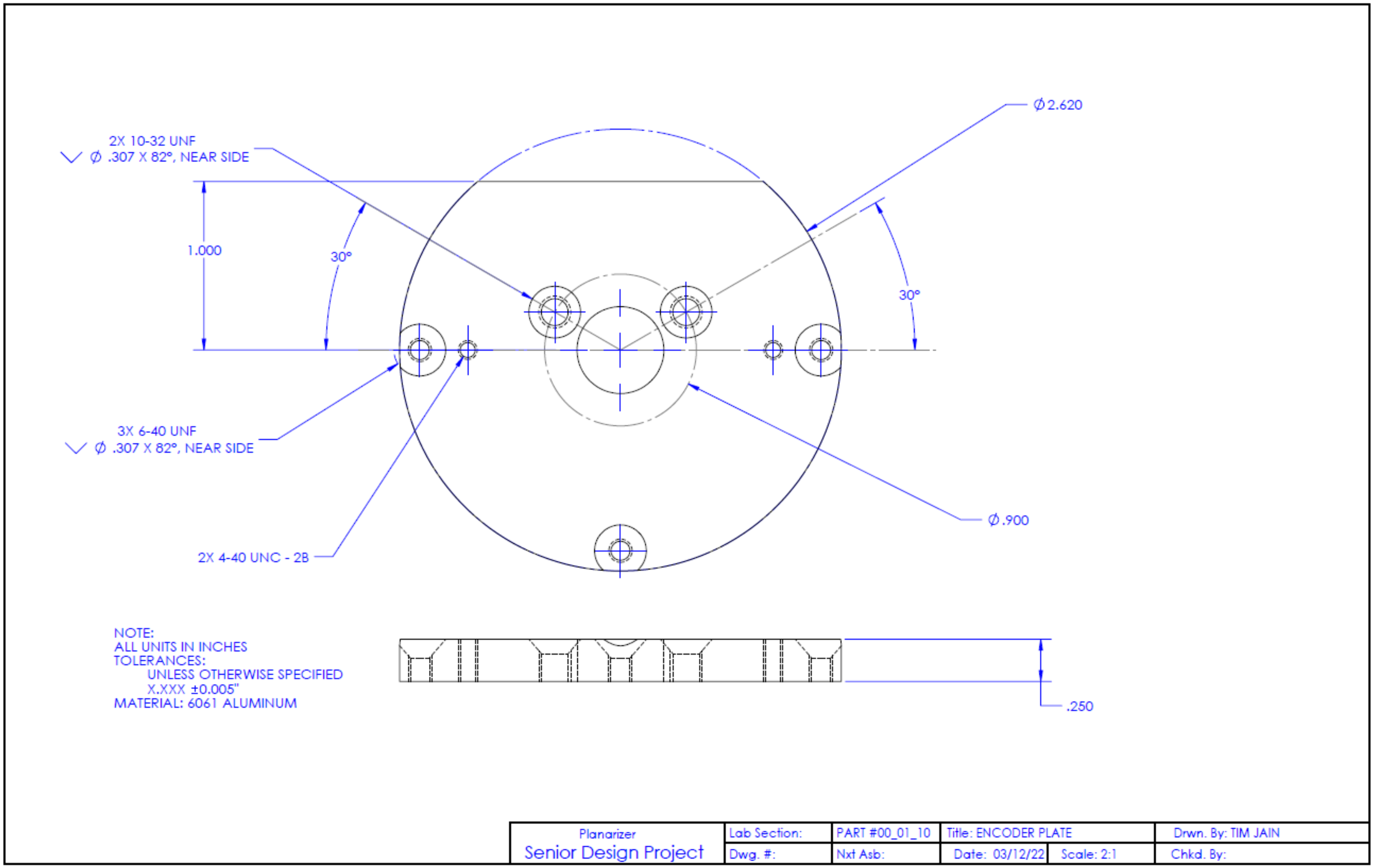
Planarizer Senior Design Project	Lab Section:	PART #00_01_06	Title: FIXED HOUSING		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/10/22	Scale: 1:2	Chkd. By:

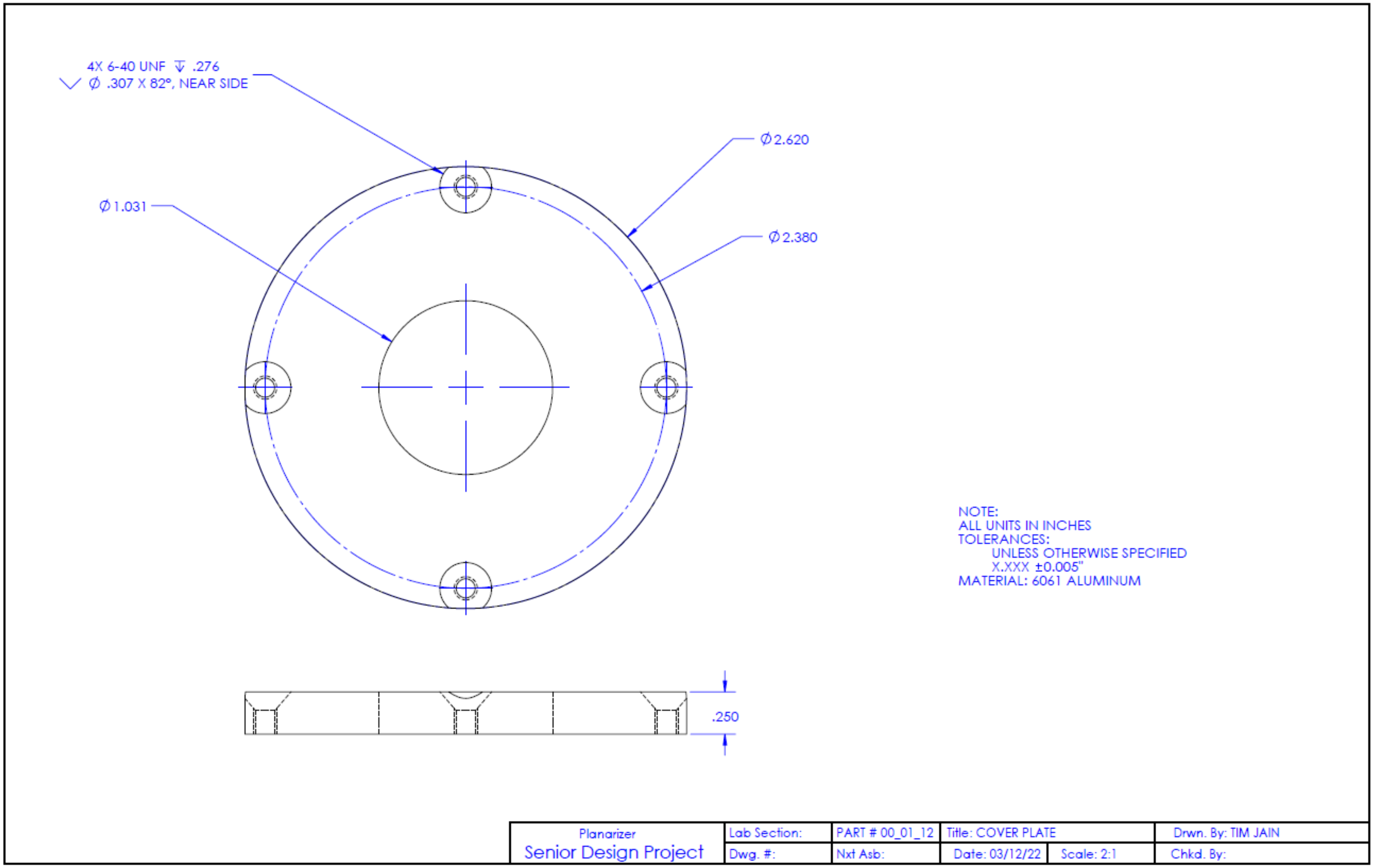


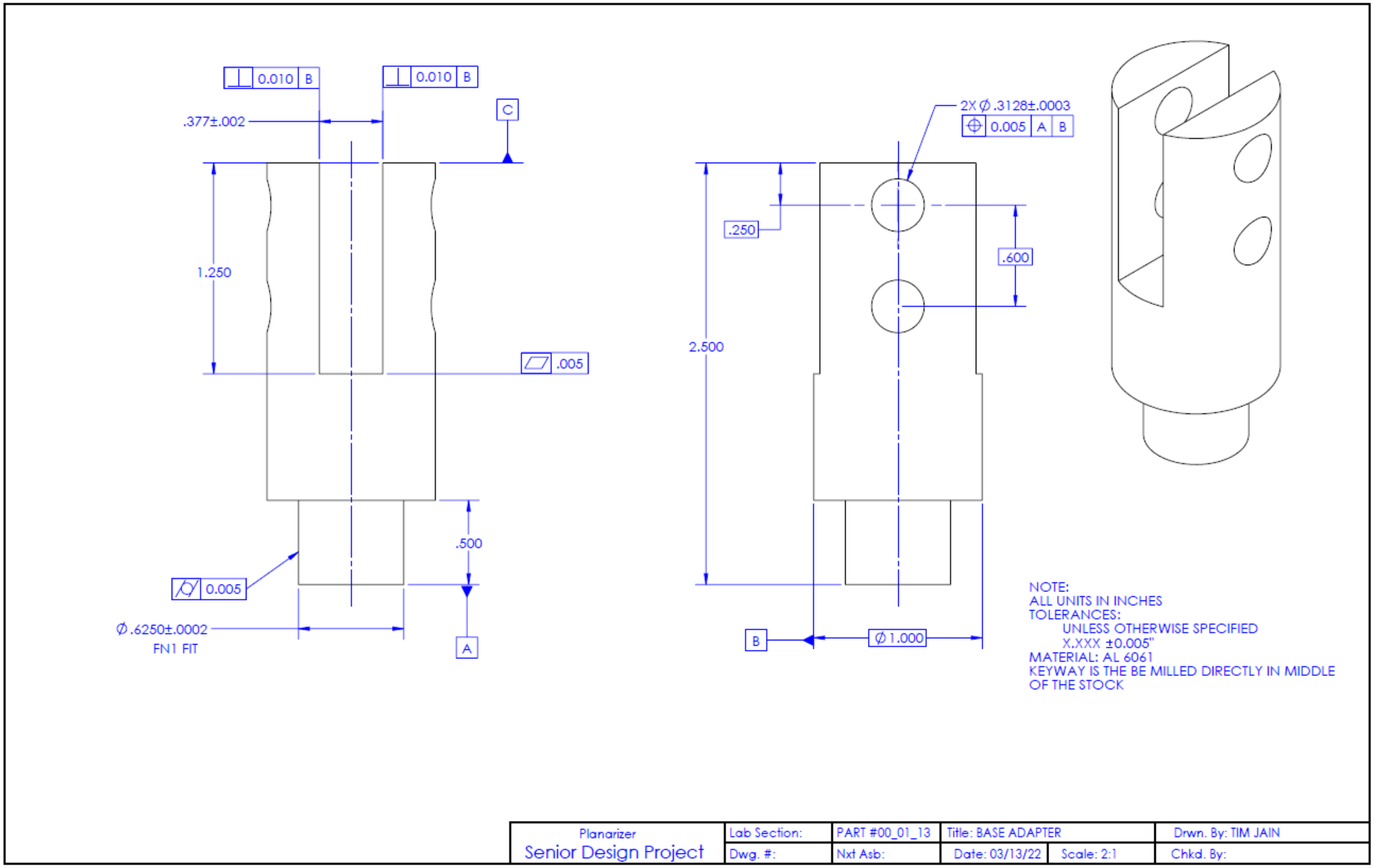
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: 6061 ALUMINUM

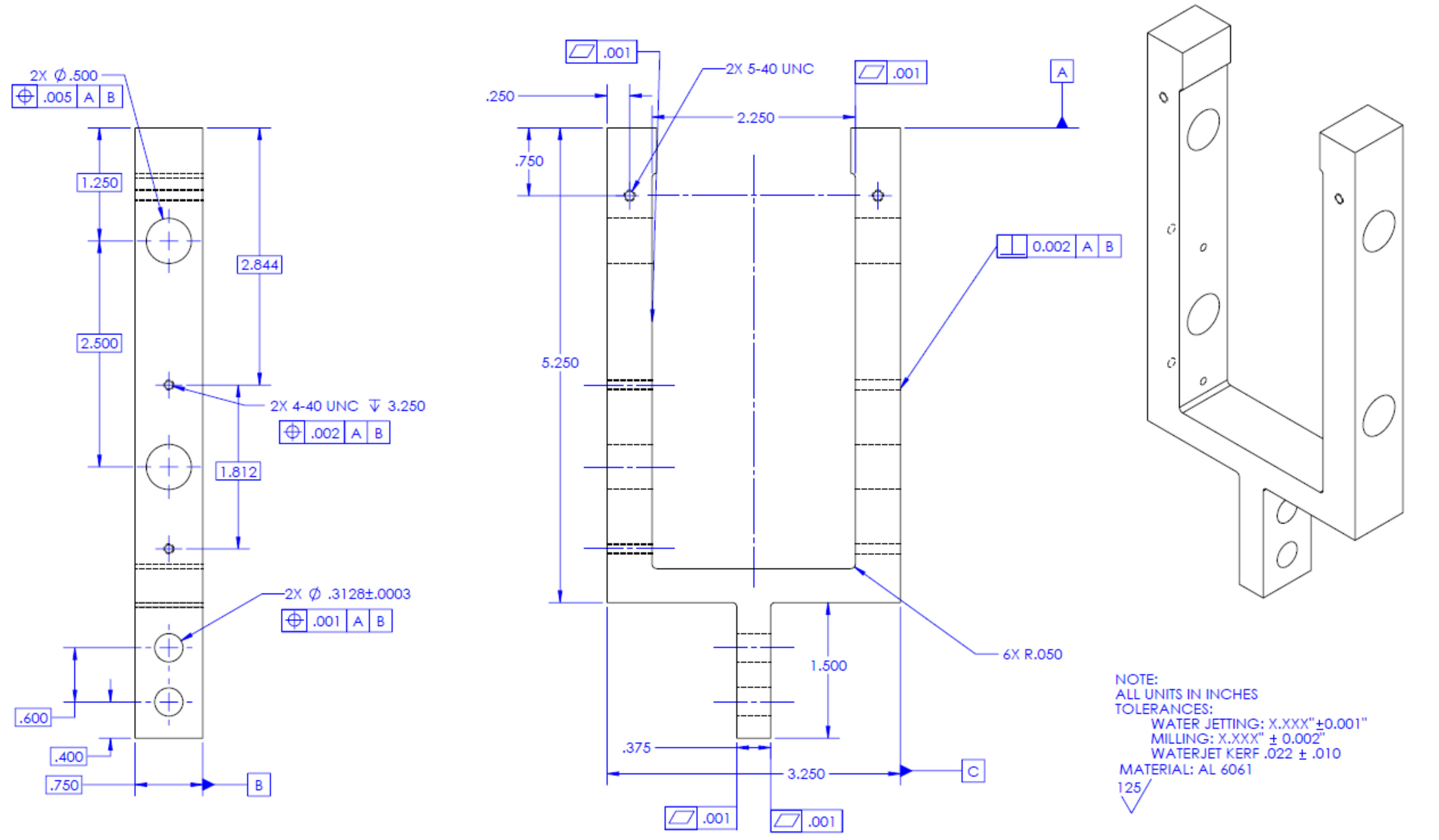
Planarizer Senior Design Project	Lab Section:	PART #00_01_07	Title: BASE SHAFT		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 12/18/21	Scale: 1:1.25	Chkd. By:

SOLIDWORKS Educational Product. For Instructional Use Only.

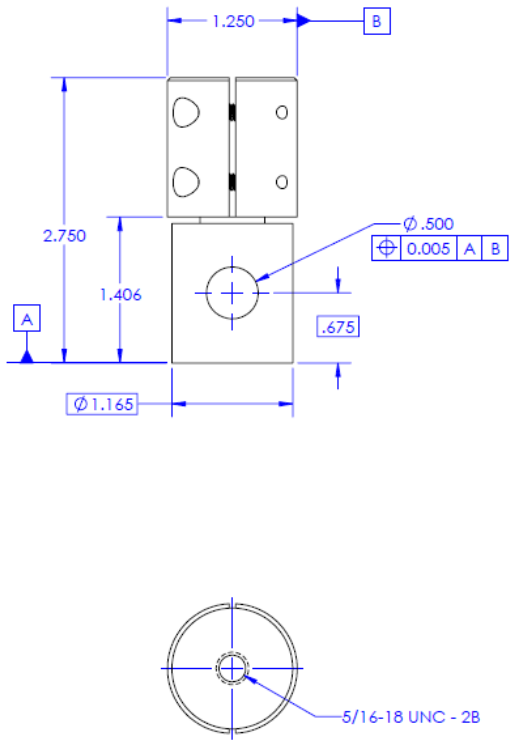

2X 10-32 UNF
⌵ Ø .307 X 82°, NEAR SIDE
Ø 2.620
1.000
30°
30°
3X 6-40 UNF
⌵ Ø .307 X 82°, NEAR SIDE
Ø .900
2X 4-40 UNC - 2B
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: 6061 ALUMINUM
.250
Planarizer
Senior Design Project
Lab Section:
Dwg. #:
PART #00_01_10
Nxt Asb:
Title: ENCODER PLATE
Date: 03/12/22
Scale: 2:1
Drwn. By: TIM JAIN
Chkd. By:

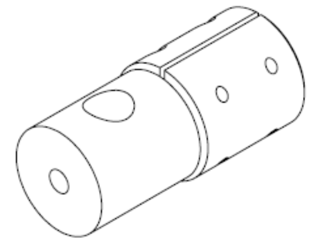

4X 6-40 UNF ⏷ .276
⌵ ∅ .307 X 82°, NEAR SIDE
∅2.620
∅1.031
∅2.380
.250
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: 6061 ALUMINUM
Planarizer
Senior Design Project
Lab Section:
Dwg. #:
PART # 00_01_12
Nxt Asb:
Title: COVER PLATE
Date: 03/12/22
Scale: 2:1
Drwn. By: TIM JAIN
Chkd. By:


0.010 B
0.010 B
.377±.002
C
1.250
.005
.500
0.005
Ø.6250±.0002
FN1 FIT
A
2X Ø.3128±.0003
0.005 A B
.250
.600
2.500
B
Ø1.000
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±0.005"
MATERIAL: AL 6061
KEYWAY IS THE BE MILLED DIRECTLY IN MIDDLE
OF THE STOCK
Planarizer
Senior Design Project
Lab Section:
Dwg. #:
PART #00_01_13
Nxt Asb:
Title: BASE ADAPTER
Date: 03/13/22
Scale: 2:1
Drwn. By: TIM JAIN
Chkd. By:

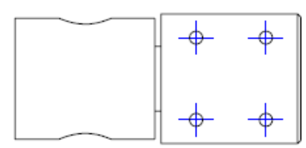


Planarizer Senior Design Project	Lab Section:	PART # 00_02_01	Title: CLEVIS YOKE		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/13/22	Scale: 1:1	Chkd. By:

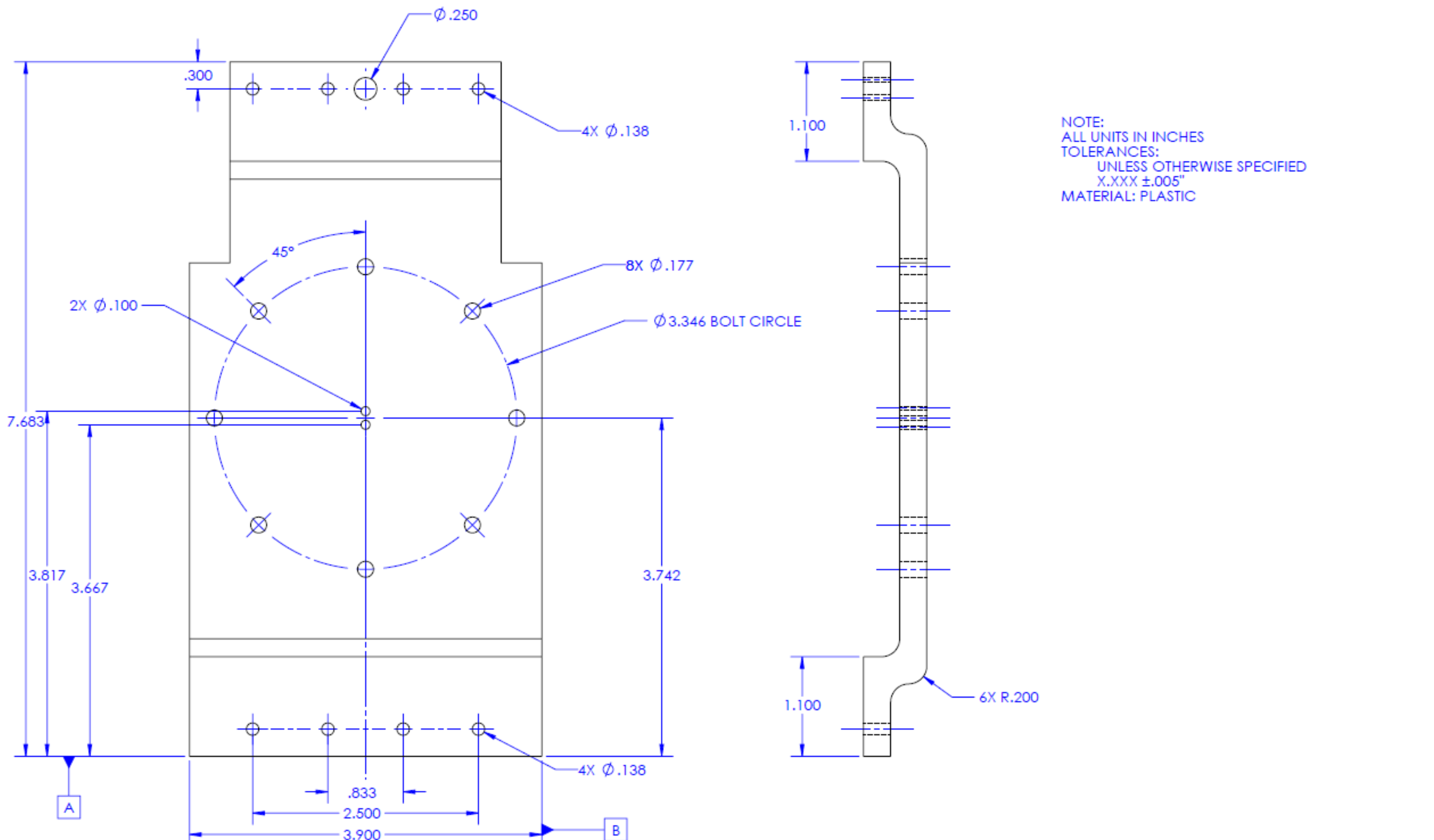




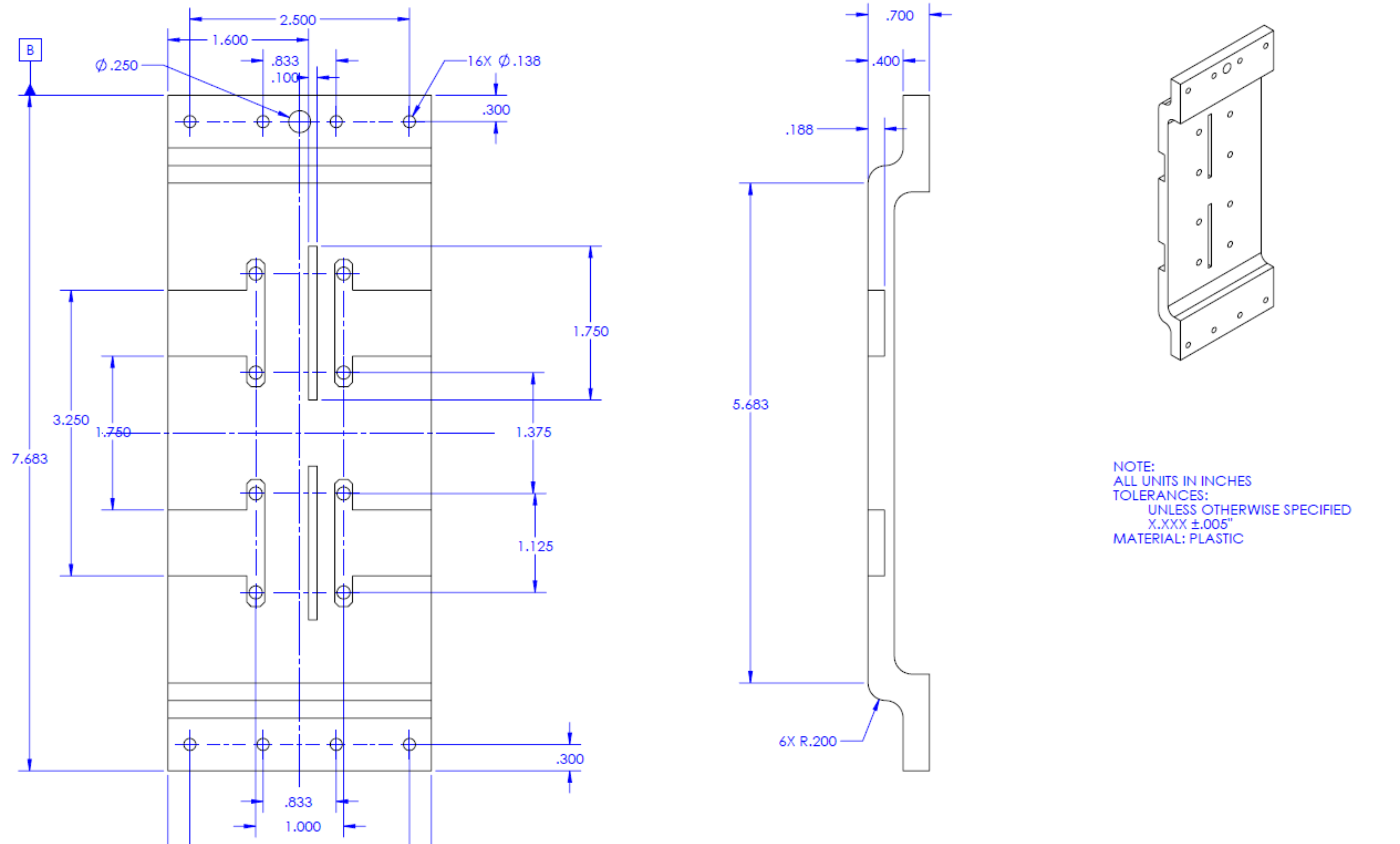
Notes:
Material: BLACK-OXIDE 1215 CARBON STEEL
TOLERANCES:
MILLING: X.XXX ± 0.005"
2 HOLES DRILLED FOR THIS PART AND DIAMETER TURNED DOWN FROM COTS MC-MASTER PART



Planarizer Senior Design Project	Lab Section:	PART # 00_03_02	Title: BOOM SHAFT END		Drwn. By: ERIC RAMOS
	Dwg. #:	Nxt Asb:	Date: 03/13/22	Scale: 1:1	Chkd. By: TIM JAIN

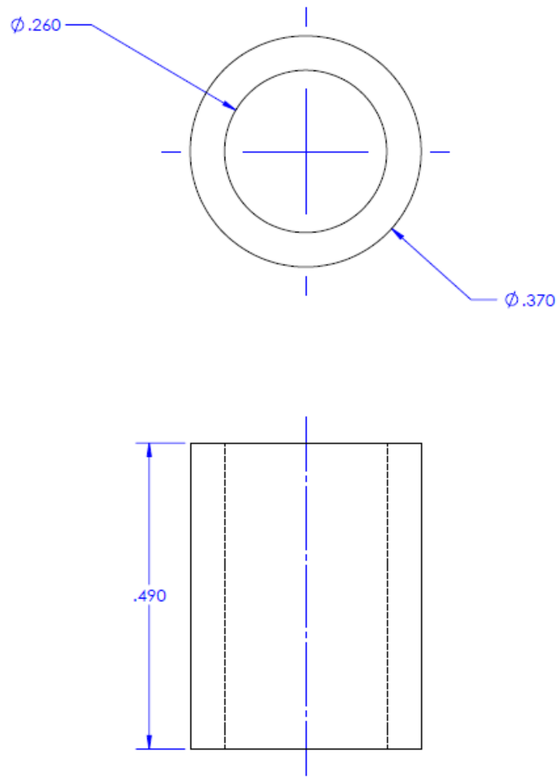


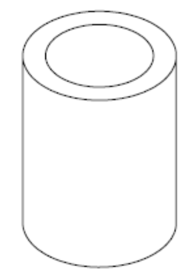
Planarizer	Lab Section:	PART # 00_04_01	Title: CAN SIDE MOUNT		Drwn. By: ERIC RAMOS
Senior Design Project	Dwg. #:	Nxt Asb:	Date:3/13/22	Scale: 1:1	Chkd. By: TIM JAIN



NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±.005"
MATERIAL: PLASTIC

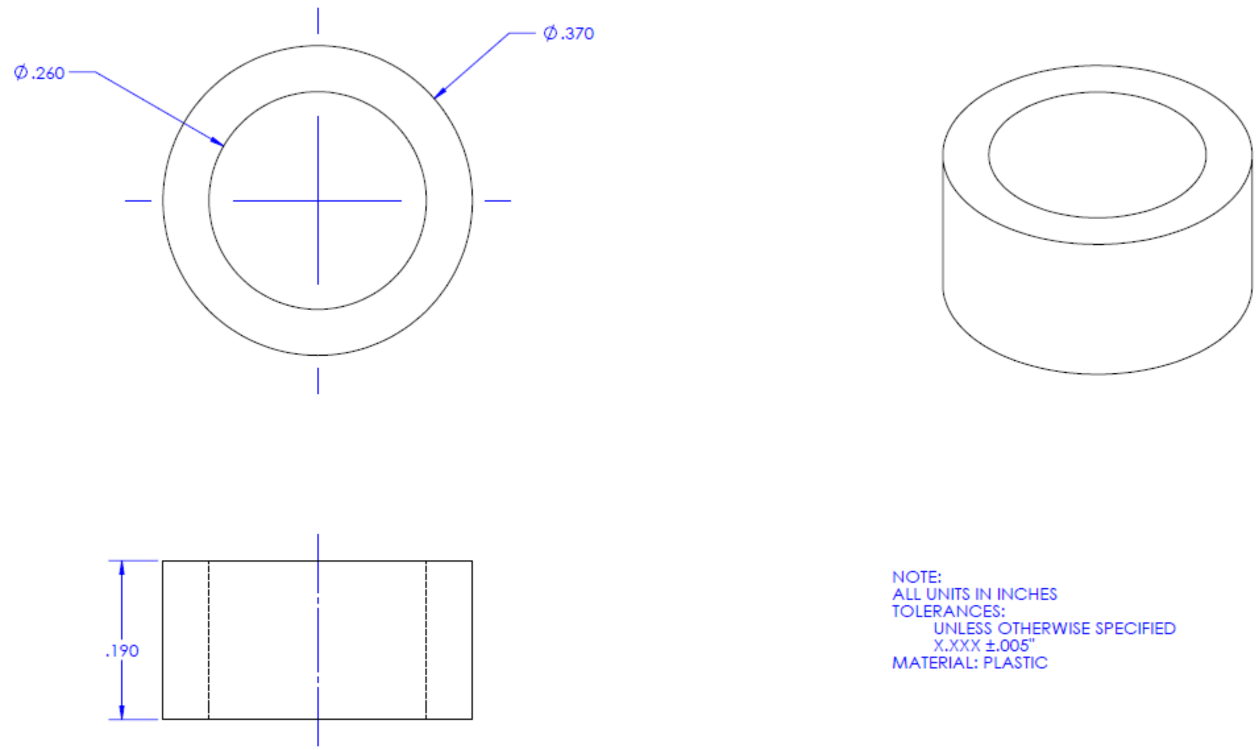
Planarizer Senior Design Project	Lab Section:	PART #: 00_04_02	Title: MAIN LEG MOUNT PLATE		Drwn. By: ERIC RAMOS
	Dwg. #:	Nxt Asb:	Date: 3/13/22	Scale: 1:1	Chkd. By: TIM JAIN





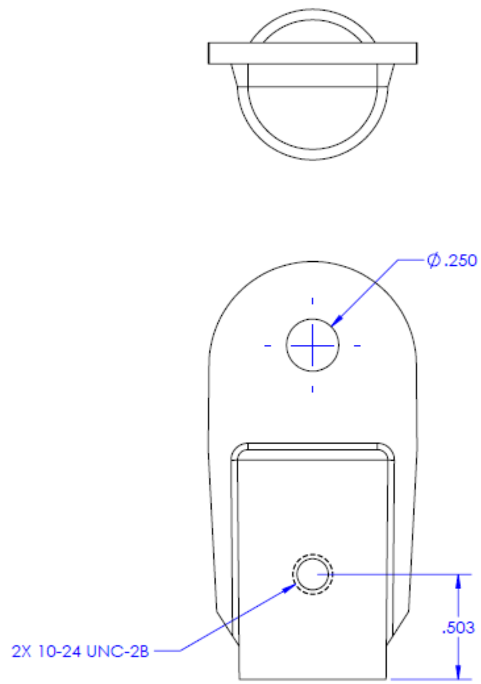
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±.005"
MATERIAL: PLASTIC

Planarizer Senior Design Project	Lab Section:	PART #00_04_03	Title: LEFT LEG MOUNT SPACER		Drwn. By: ERIC RAMOS
	Dwg. #:	Nxt Asb:	Date: 03/14/22	Scale: 6:1	Chkd. By: TIM JAIN



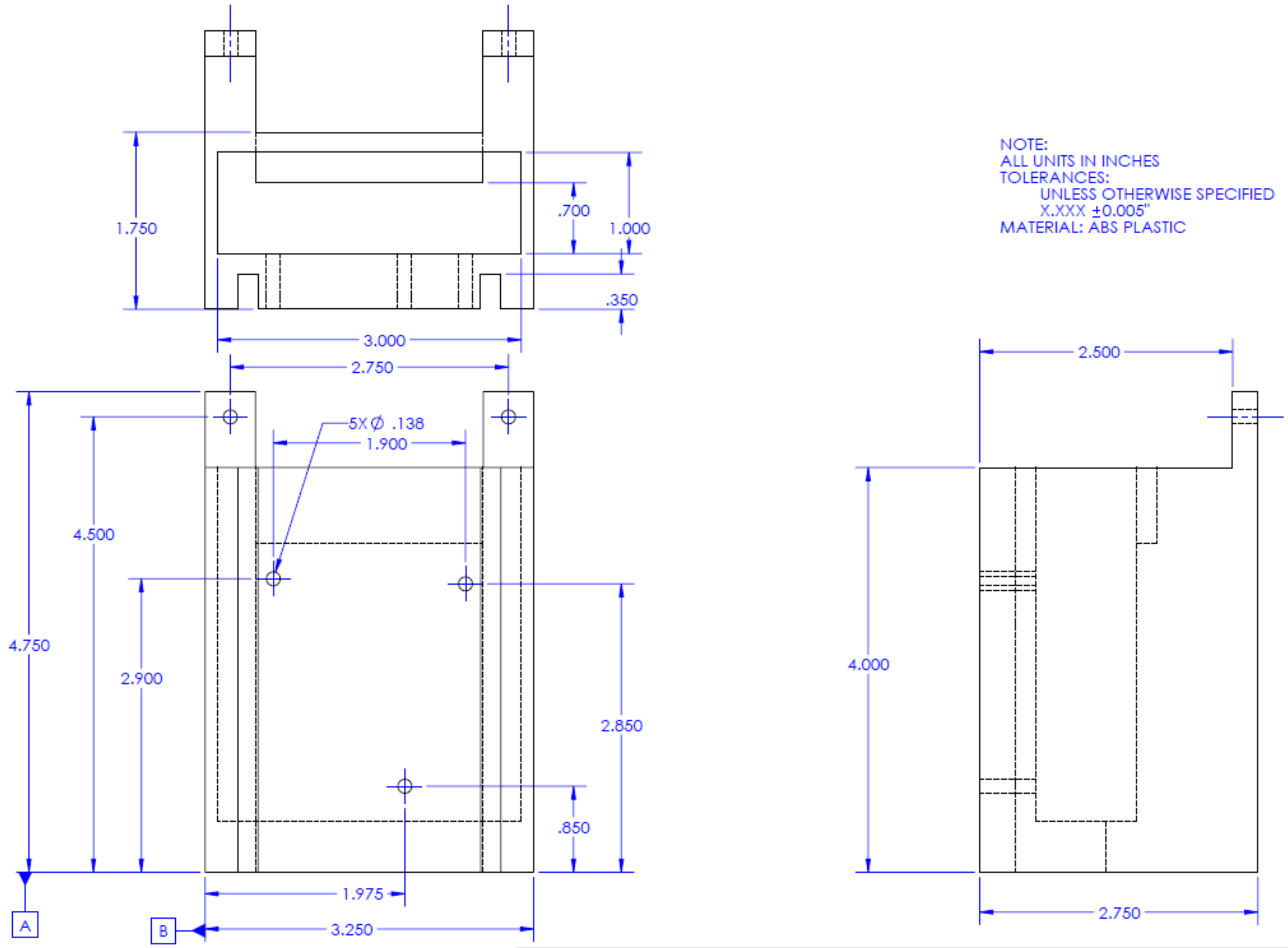
NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX ±.005"
MATERIAL: PLASTIC

Planarizer	Lab Section:	PART # 00_04_04	Title: RIGHT LEG MOUNT SPACER		Drwn. By: ERIC RAMOS
Senior Design Project	Dwg. #:	Nxt Asb:	Date: 3/14/22	Scale: 8:1	Chkd. By: TIM JAIN



NOTES:
MATERIAL: CARBON FIBER
TOLERANCES
X.XXX ± .005"
HOLE ENLARGED ON THIS PART
TAPPED HOLES CREATED, TAP FROM BOTH SIDES

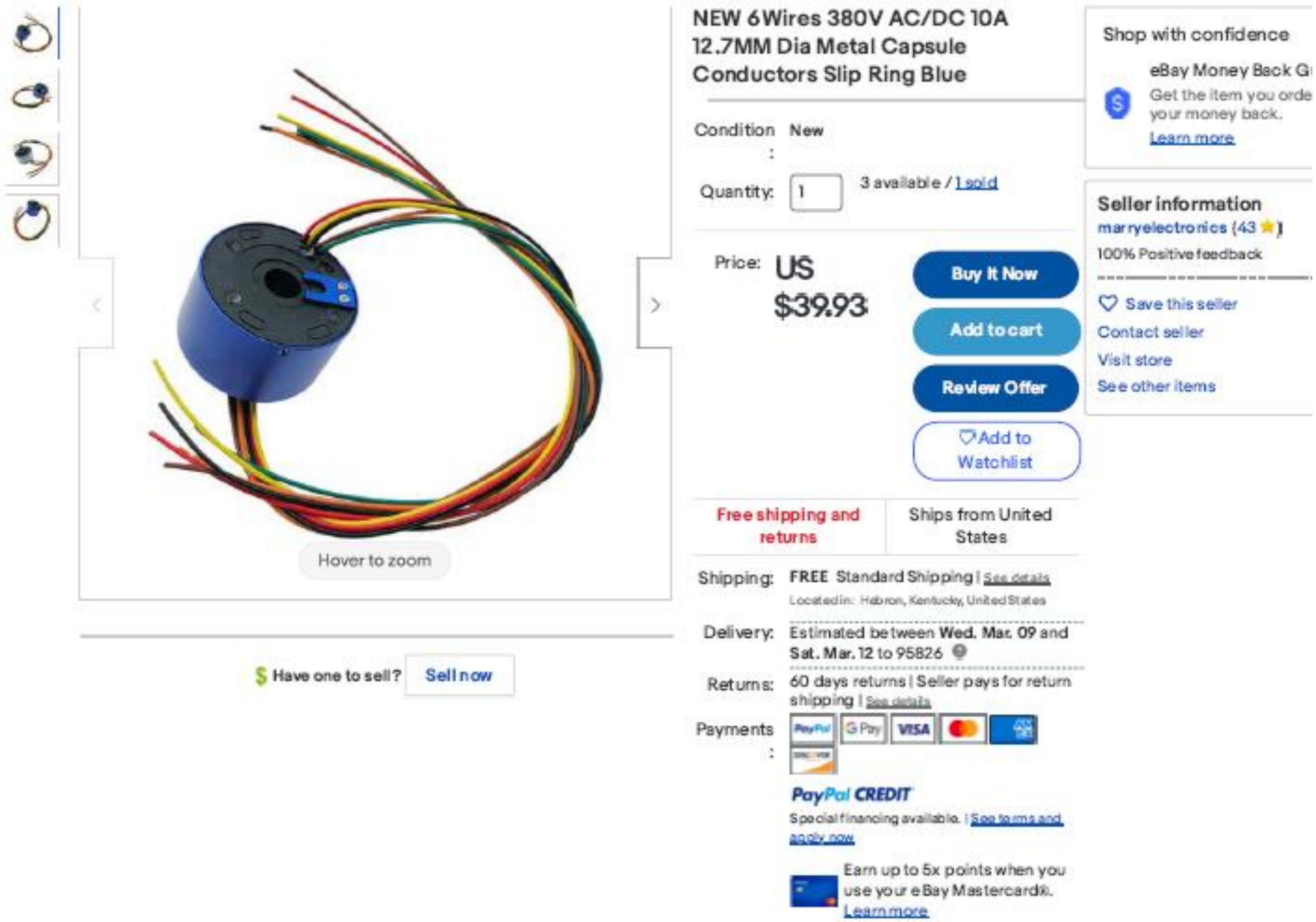
Planarizer Senior Design Project	Lab Section:	PART #00_04_06	Title: TUBE CONNECTOR	Drwn. By: ERIC RAMOS
	Dwg. #:	Nxt Asb:	Date: 3/12/22 Scale: 2:1	Chkd. By: TIM JAIN



NOTE:
ALL UNITS IN INCHES
TOLERANCES:
UNLESS OTHERWISE SPECIFIED
X.XXX $\pm$0.005"
MATERIAL: ABS PLASTIC

Planarizer Senior Design Project	Lab Section:	PART # 00_05_01	Title: DAQ MOUNT PLATE		Drwn. By: TIM JAIN
	Dwg. #:	Nxt Asb:	Date: 03/14/22	Scale: 1:1	Chkd. By:

Appendix V: Product Specifications
Slip Ring



Product Description

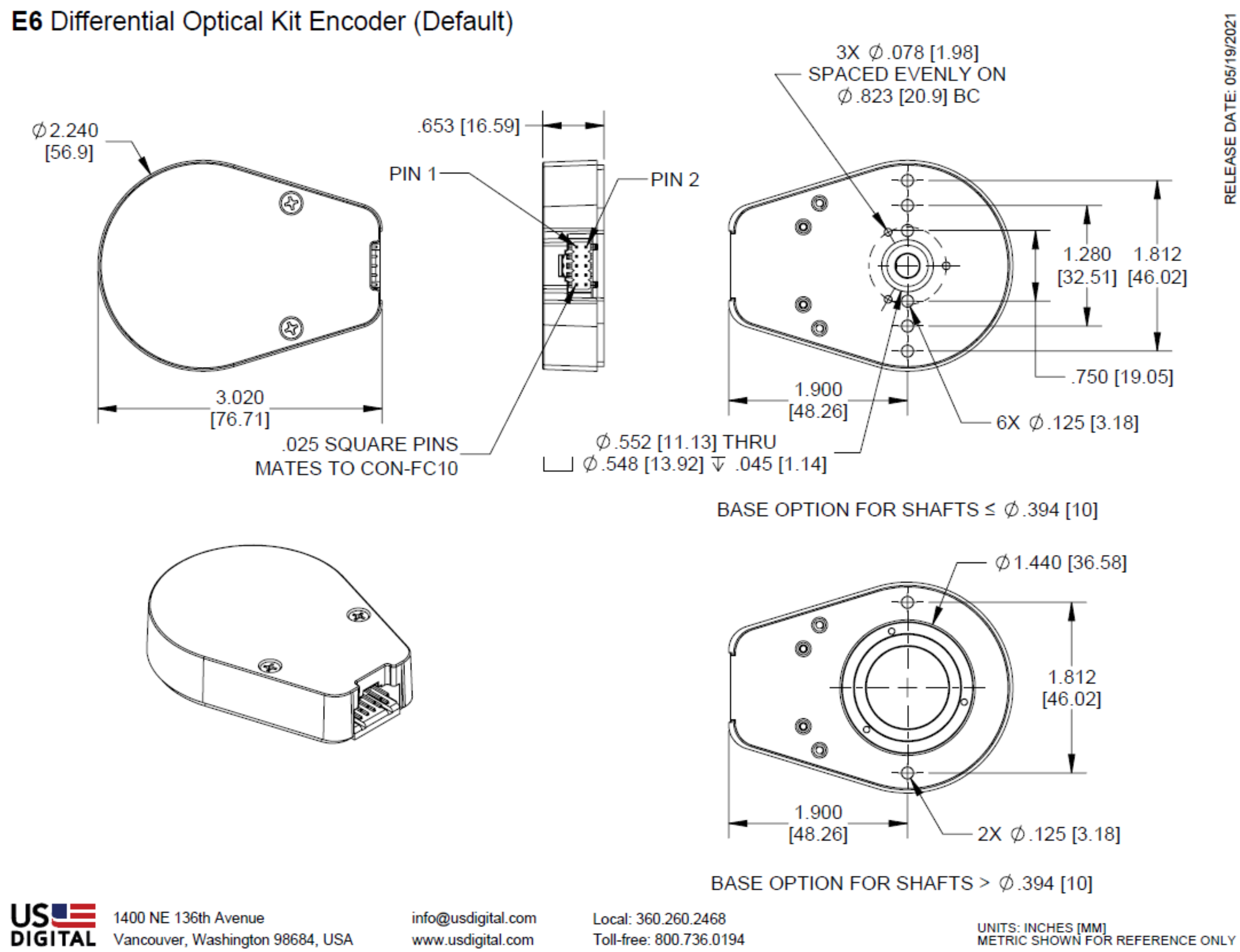
Specifications:

Pathway: 6 Wires
Cable length: 200MM
Hole Dia: 12.7MM
Body Dia: 54MM
Rated voltage:380V

Rated Current:10A per circuit
Material: Metal and plastic
Color: Blue & Black
Speed: 300 rpm

Rated current: 10A/circui
Protection Level: IP54
Rated voltage: 220V
Contact materials: precious metals
Insulation resistance: 500M@500VDC
Shell material: engineering materials
Electrical Noise: 10m@ 6VDC, 50mA, 5Rpm
Torque: 0.01N.M
Working life: more than 5 million revolutions
Bearing type: 6704ZZ bearing steel
Working Temperature: -40 ~+80
Wire Specification: AWG#17 Teflon Wire UL
Relative humidity: 60%
Wire Length: 300mm
Mechanical vibration: MIL-SID-810E
Environmental Certification: RoHS Certification
CE certification: YES

Encoder


E6 Differential Optical Kit Encoder (Default)
RELEASE DATE: 05/19/2021
Ø2.240
[56.9]
.653 [16.59]
PIN 1
PIN 2
3X Ø.078 [1.98]
SPACED EVENLY ON
Ø.823 [20.9] BC
1.280
[32.51]
1.812
[46.02]
.750 [19.05]
3.020
[76.71]
1.900
[48.26]
6X Ø.125 [3.18]
.025 SQUARE PINS
MATES TO CON-FC10
Ø.552 [11.13] THRU
Ø.548 [13.92] ↧ .045 [1.14]
BASE OPTION FOR SHAFTS ≤ Ø.394 [10]
Ø1.440 [36.58]
1.812
[46.02]
1.900
[48.26]
2X Ø.125 [3.18]
BASE OPTION FOR SHAFTS > Ø.394 [10]
1400 NE 136th Avenue
Vancouver, Washington 98684, USA
info@usdigital.com
www.usdigital.com
Local: 360.260.2468
Toll-free: 800.736.0194
UNITS: INCHES [MM]
METRIC SHOWN FOR REFERENCE ONLY

Specifications

ENVIRONMENTAL

PARAMETER	VALUE	UNITS
Operating Temperature (CPR < 3600)	-40 to 100	C
Operating Temperature (CPR ≥ 3600)	-25 to 100	C
Vibration (5Hz to 2kHz)	20	G
Electrostatic Discharge Single-ended (-A, -S version), IEC 61000-4-2 Differential (-D, -L version), Human Body Model	 ± 4 ± 2	 kV

MECHANICAL

PARAMETER	VALUE	UNITS
Max. Shaft Axial Play	±0.010	in.
Max. Shaft Runout	0.004 T.I.R.	in.
Max. Acceleration	250000	rad/sec²
For CPR ≤ 2500: Max. RPM (1) Max. A/B Frequency e.x. CPR=2500, Max. RPM=7200 e.x. CPR=100, Max. RPM=60000	 minimum value of ((18 x 10^6) / CPR) and (60000) 300	 RPM kHz
For CPR = 3600, 4000, 4096, 5000: Max. RPM (1) Max. A/B Frequency	 (21.6 x 10^6) / CPR 360	 RPM kHz
For CPR = 7200, 8000, 8192, 10000: Max. RPM (1) Max. A/B Frequency	 (43.2 x 10^6) / CPR 720	 RPM kHz
Typical Product Weight Single-Ended (S-option) Differential (D-option, L-option)	 1.55 1.83	 oz.
Codewheel Moment of Inertia	8.9 x 10^-5 for bore < 12mm 4.0 x 10^-4 for bore ≥ 12 mm	oz-in-s²
Hub Set Screw	#3-48 or #4-48	
Hex Wrench Size	0.050	in.
Encoder Base Plate Thickness	0.135	in.
3 Mounting Screw Size	#0-80	
2 Mounting Screw Size	#2-56 or #4-40	
3 Screw Bolt Circle Diameter (2)	0.823 ± 0.005	in.
2 Screw Bolt Circle Diameter	0.750 ± 0.005	in.
Required Shaft Length (3) With E-option (2) With H-option	0.445 to 0.570 0.445 to 0.750 > 0.445	in.
Index Alignment to Hub Set Screw	180 Typical	degrees

(1) 60000 RPM is the maximum rpm due to mechanical considerations. The maximum RPM due to the module's maximum frequency response is dependent upon the module's resolution (CPR).

(2) Only for shaft diameters < 0.472".

(3) Add 0.125" to all required shaft lengths when using M-option.

TORQUE SPECIFICATIONS

PARAMETER	VALUE	TORQUE
Hub Set Screw	2-3	in-lbs
Cover Screw	2-4	in-lbs
Base Mounting Screw (#0-80)	1-2	in-lbs
Base Mounting Screw (#2-56)	2-3	in-lbs
Base Mounting Screw (#4-40)	4-6	in-lbs
Adapter Plate Mounting Surface (#2-56 screws)	2-3	in-lbs
Adapter Plate Mounting Surface (#4-40 screws)	4-6	in-lbs
Module Mounting Screw	3.5-4	in-lbs

DIFFERENTIAL ELECTRICAL

- Specifications apply over the entire operating temperature range.
- Typical values are specified at Vcc = 5.0Vdc and 25°C.
- For complete details, see the EM1 *(https://www.usdigital.com/products/encoders/incremental/modules/em1/)* and EM2 *(https://www.usdigital.com/products/encoders/incremental/modules/em2/)* product pages.

PARAMETER	MIN.	TYP.	MAX.	UNITS	CONDITIONS
Supply Voltage	4.5	5.0	5.5	V	
Supply Current		29	36	mA	CPR < 1000, no load
		56	65	mA	CPR ≥ 1000 and < 3600, no load
		74	88	mA	CPR ≥ 3600, no load
Low-level Output		0.2	0.4	V	I_{OL} = 20mA max.
High-level Output	2.4	3.4		V	I_{OH} = -20mA max.
Differential Output Rise/Fall Time			15	nS	

PIN-OUTS

5-PIN SINGLE-ENDED (1)		10-PIN DIFFERENTIAL, STANDARD (2)		10-PIN DIFFERENTIAL (L-OPTION) (2)(3)		10-PIN SINGLE-ENDED (A-OPTION) (2)(3)	
Pin	Description	Pin	Description	Pin	Description	Pin	Description
1	Ground	1	Ground	1	No connection	1	A channel
2	Index	2	Ground	2	+5VDC power	2	+5VDC power
3	A channel	3	Index-	3	Ground	3	Ground
4	+5VDC power	4	Index+	4	No connection	4	No connection
5	B channel	5	A- channel	5	A- channel	5	No connection
		6	A+ channel	6	A+ channel	6	Ground
		7	+5VDC power	7	B- channel	7	+5VDC power
		8	+5VDC power	8	B+ channel	8	B+ channel
		9	B- channel	9	Index-	9	+5VDC power
		10	B+ channel	10	Index+	10	Index

(1) 5-pin single-ended mating connector is CON-FC5 *(https://www.usdigital.com/products/accessories/connectors/con-fc5/)*.
(2) 10-pin differential mating connector is CON-FC10 *(https://www.usdigital.com/products/accessories/connectors/con-fc10/)*.
(3) Broadcom / Avago compatible version.

1. Centering Tool

The centering tool is only included with the **-3** packaging option. It has to be ordered separately for other packaging options.

Part #: CTOOL - (Shaft Diameter)
Description: This reusable tool provides a simple method for accurately centering the **E6** base onto the shaft.

It is recommended for the following situations:

- When using mounting screws smaller than #4-40.
- When the position of the mounting holes is in question.
- When using the 3-hole mounting pattern.
- When using the **T**-option transfer adhesive.

2. Hex Tool

Depending on the order quantity and packaging option, either a hex driver or hex wrench is included.

Part #: HEXD-050
Description: Hex driver, .050" flat-to-flat for #3-48 or #4-48 set screws. Only included with **-B** or **-1** packaging options.

Part #: HEXW-050
Description: Hex wrench, .050" flat-to-flat for #3-48 or #4-48 set screws. Only included with **-2** or **-3** packaging options.

3. Spacer Tool

A spacer tool is included for all packaging options.

Part #: SPACER-E6S
Description: For shaft sizes < 0.472"

Part #: SPACER-E6L
Description: For shaft sizes 12mm to 1"

4. Screws

Part #: SCREW-080-250-PH
Description: Pan Head, Philips #0-80 UNF x 1/4"
Use: Base Mounting
Quantity Required: 3
Screws are not included

Part #: SCREW-256-250-PH
Description: Pan Head, Philips #2-56 UNC x 1/4"
Use: Base Mounting
Quantity Required: 2
Screws are not included

Part #: SCREW-348-125-SS
Description: Socket Head Set Screw, 3-48 UNC x 1/8"
Use: Hub/Disk Mounting for 12mm - 1" Bore
Quantity Required: 2
Screws are included

Part #: SCREW-440-250-PH
Description: Pan Head, Philips #4-40 UNC x 1/4"
Use: Base Mounting
Quantity Required: 2
Screws are not included

Part #: SCREW-440-500-PH
Description: Pan Head, Phillips #4-40 UNC x 1/2"
Use: Module Mounting

Quantity Required: 2
Screws are included

Part #: SCREW-440-625-FH
Description: Flat Head, Phillips 4-40 UNC x 5/8"
Use: Cover Mounting
Quantity Required: 2
Screws are included

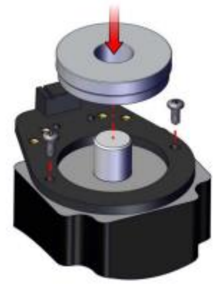
Part #: SCREW-448-063-SS
Description: Socket Head Set Screw, 4-48 UNC x 1/16"
Use: Hub/Disk Mounting for 5/16" - 10mm Bore
Quantity Required: 1
Screw is included

Part #: SCREW-448-125-SS
Description: Socket Head Set Screw, 4-48 UNC x 1/8"
Use: Hub/Disk Mounting for 2mm - 1/4" Bore
Quantity Required: 1
Screw is included

E6 Assembly Instructions for Shafts > 0.394" (10mm)

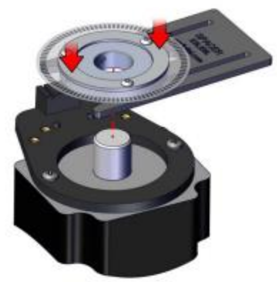
Step 1:

Place encoder base onto mounting surface. Slip centering tool over the shaft and into the center hole of the base. While holding pressure on the centering tool, tighten mounting screws. Remove centering tool.



Step 2:

Push the spacer tool onto the bottom section of the hubdisk assembly. Slip hubdisk assembly onto shaft and slide down until spacer tool bottoms out against encoder base.



Step 3:

Tighten set screw with provided hex wrench while pressing down on hub. Remove spacer tool.

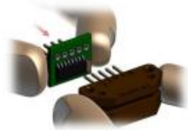
E6 Assembly Instructions for Shafts > 0.394" (10mm)

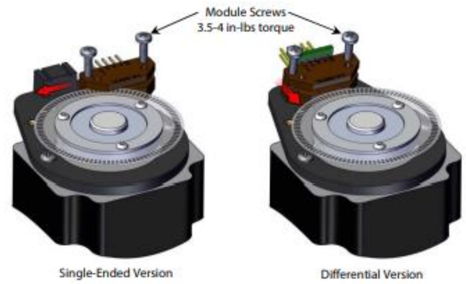
Step 4:

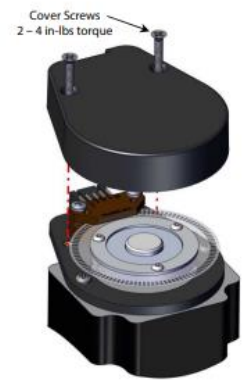
Slip optical module into position until the two alignment pins slip into holes of module (thick side of module towards bottom). Secure with two 4-40 x 1/2" screws (supplied).

Differential version only:
Press line driver onto module pins until it reaches the end of its motion.

Caution!
To avoid injury make sure that the line driver is held properly (as shown) during installation, module pins are sharp!

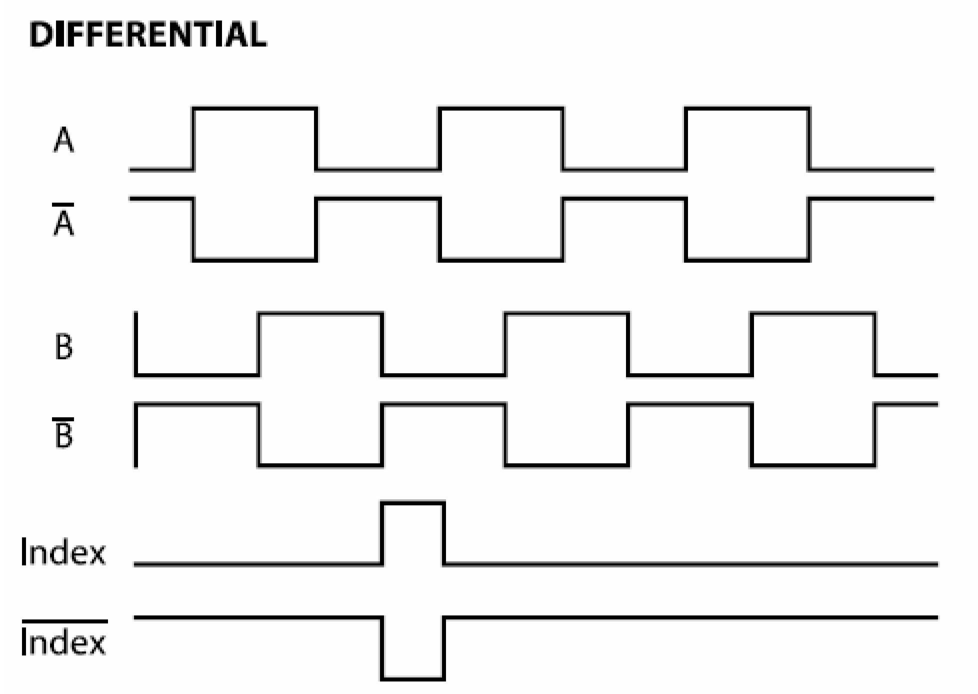






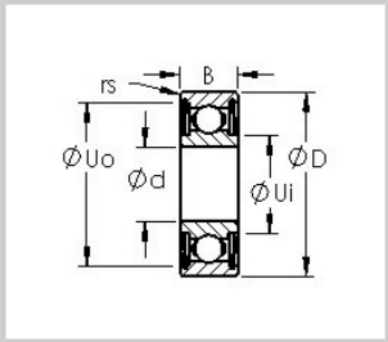
Step 5:

Place cover over assembly and secure with two 4-40 5/8" flat head screws (supplied).


DIFFERENTIAL
A
$\overline{A}$
B
$\overline{B}$
Index
$\overline{Index}$

Carbon Fiber Booms

Length	48"
Wall Thickness	0.05"
Shape	Round
Inner Diameter	0.400"
Outside Diameter	0.500"
Tube Finish	Tooled
Ply Orientation	UD 0
Max Temperature	200 F
Fiber Modulus	Standard (33 Msi)
Composition	Solid CF (All Uni Directional)
Approx. Weight	0.186 lb
Approx. Density	0.056 lb/in^3



Part Number: R16ZZ R
Series Ball Bearing

Product Details

Specifications

Bearing Type	Shielded	
Bore Dia (d)	1.0000	in
Outer Dia (D)	2.0000	in
Radius (min) (rs)	0.031	in
Ball Qty	10	
Ball Dia (Dw)	0.2500	in
Width (B)	0.5000	in
Dynamic Load Rating (Cr)	2,652	lbs
Static Load Rating (Cor)	1,307	lbs
Weight (g)	87.00	grams
Precision	A1	
Standard Clearance	C0	
Material	52100 Chrome steel (or equivalent)	

* Also available in Stainless Steel, add prefix \"S\"

* ABEC Grades 1, 3, 5, 7, and 9 are available.

* Two metal shields = (ZZ), also available with a single metal shield = (Z).

Appendix W: DAQ Documentation, Electrical Connections, State Transition Diagram, Task Diagram

DAQ Documentation

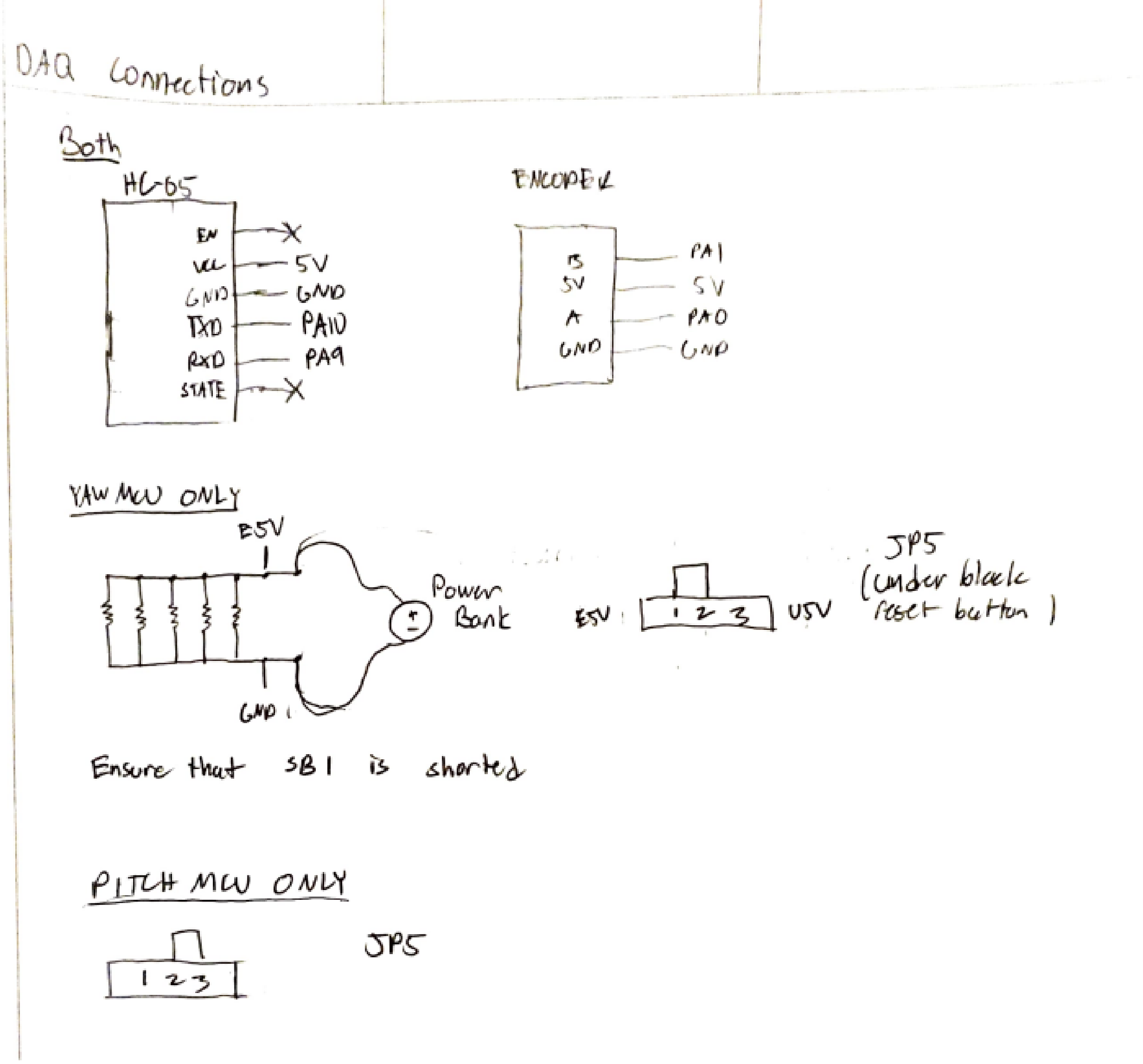
The github page can be found at :

https://github.com/malkstik/Planarizer-DAQ

The full documentation can be found at :

https://malkstik.github.io/Planarizer-DAQ/

Electrical Connections



All connections are labeled on the wires and pins. PA1 and PA0 are both available on the Arduino shield as A1 and A0 respectively. PA10 and PA9 are D2 and D8 respectively on the Arduino shield. Any GND or 5V pin on the Arduino shield may be used for corresponding connections. By default the JP5 connections are correct. For more details refer to the figures below:

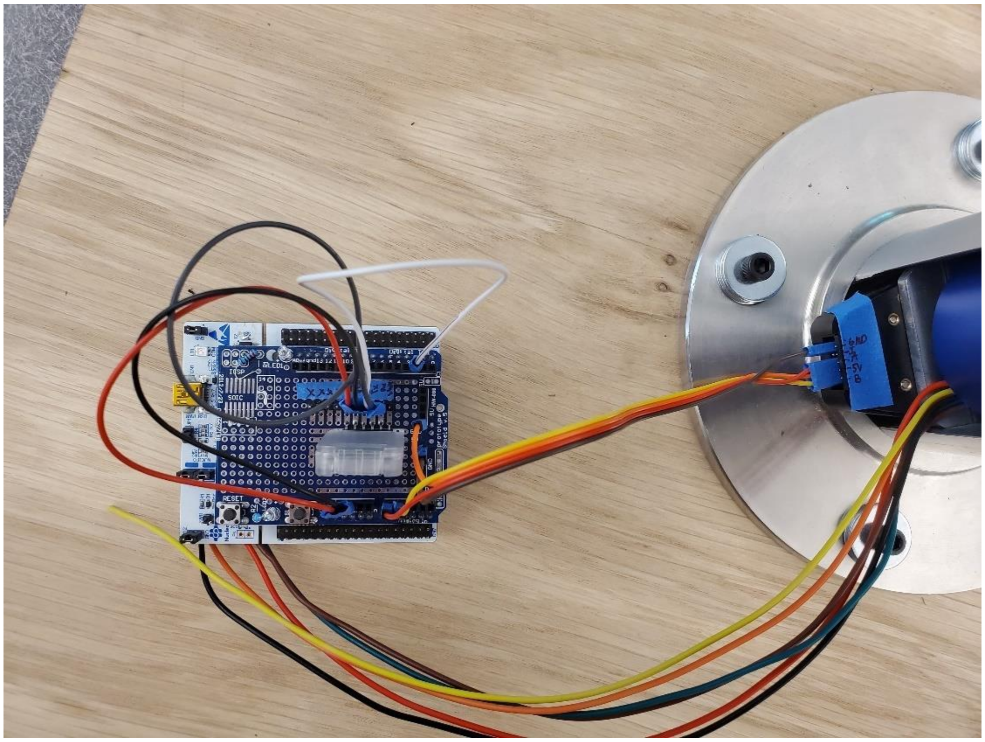


Figure 1: Yaw MCU connections

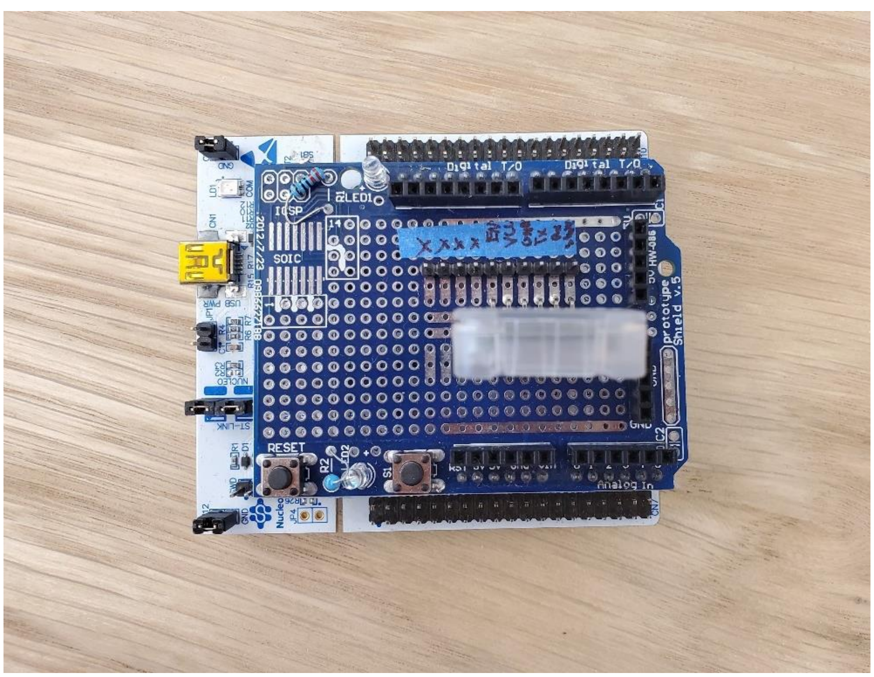


Figure 2: Yaw MCU without wires connected

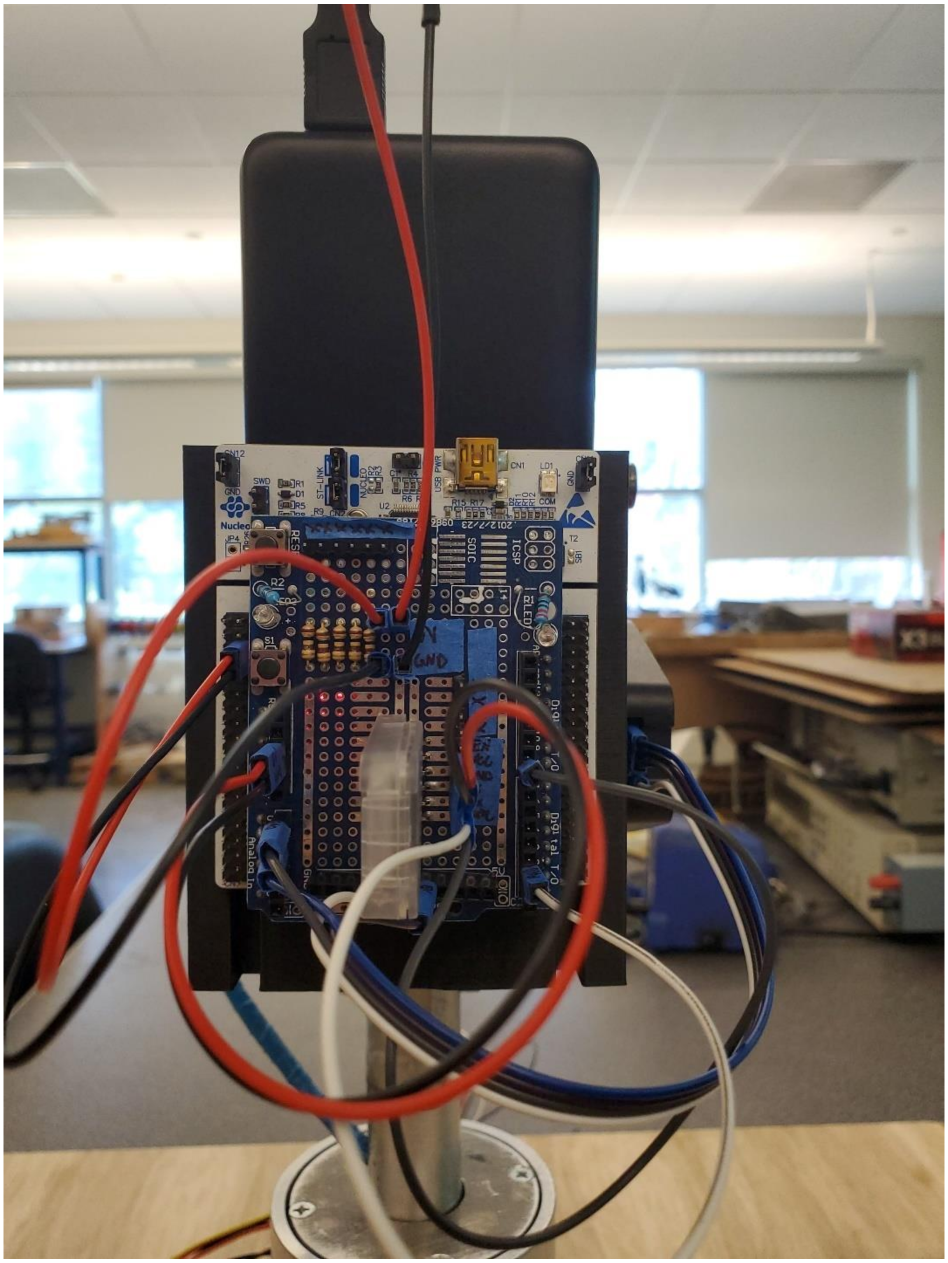


Figure 3: Pitch MCU connections

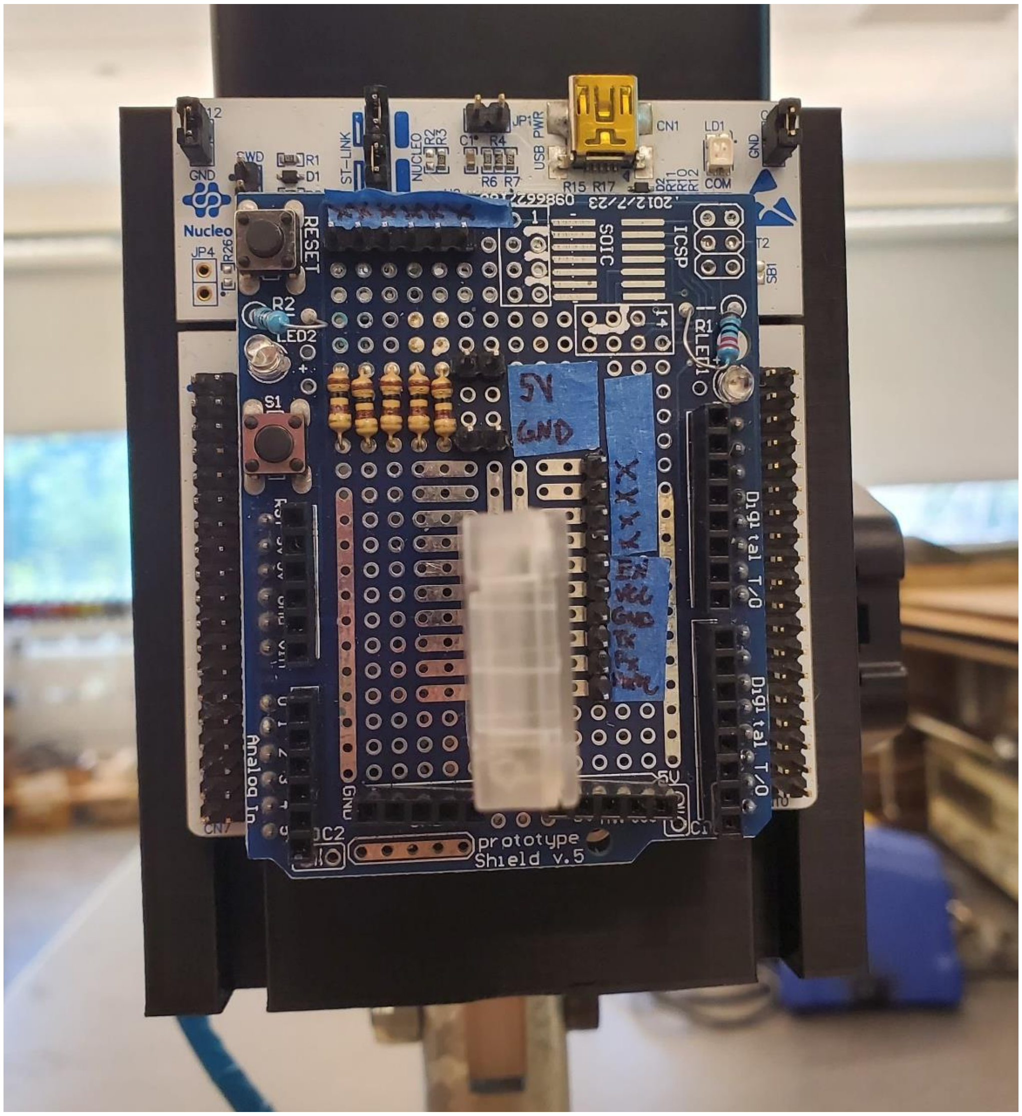


Figure 4: Pitch MCU without wires connected

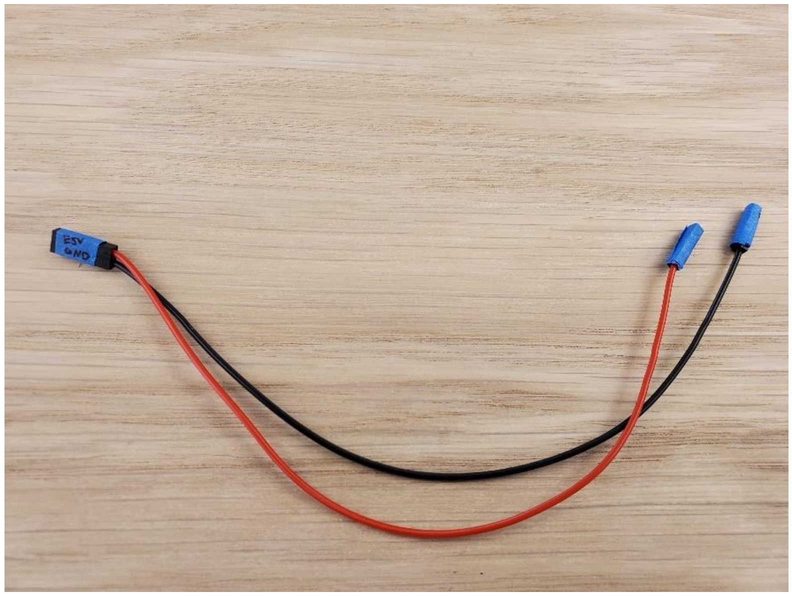


Figure 5: Power cable. On the Pitch MCU, use this to connect E5V and GND (on Nucleo) to 5V and GND pins right next to resistor circuit. These are the pins labeled on blue tape. The specific set of pins (left/right) do not matter.

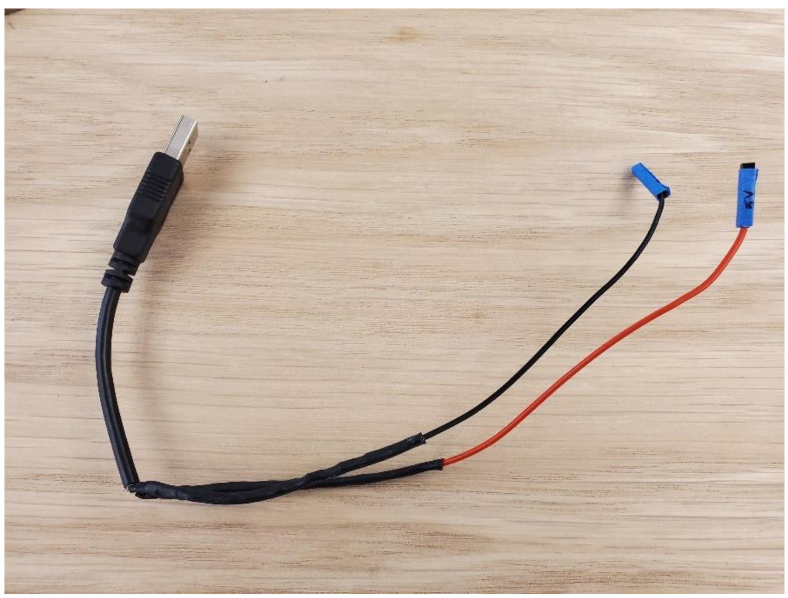


Figure 6: Power bank cable. Connect USB side to power bank. Connect 5V and GND to 5V and GND pins right next to resistor circuit. These are the pins labeled on blue tape. The specific set of pins (left/right) do not matter.

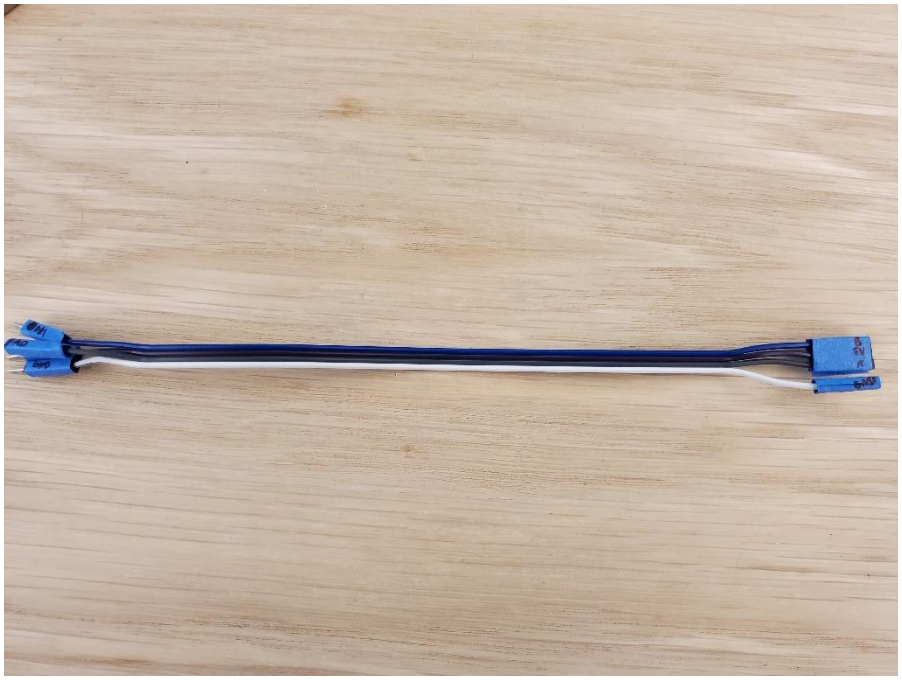


Figure 7: Encoder Cables. Connect side labeled B/5V/A/GND to encoder. Connect side labeled PA0/PA1/5V/GND to Arduino shield. The 5V and GND can go to any part on the Arduino shield that has 5V and GND written in silk screen. PA0 and PA1 connect to the pins labeled A0 and A1 on the Arduino shield.

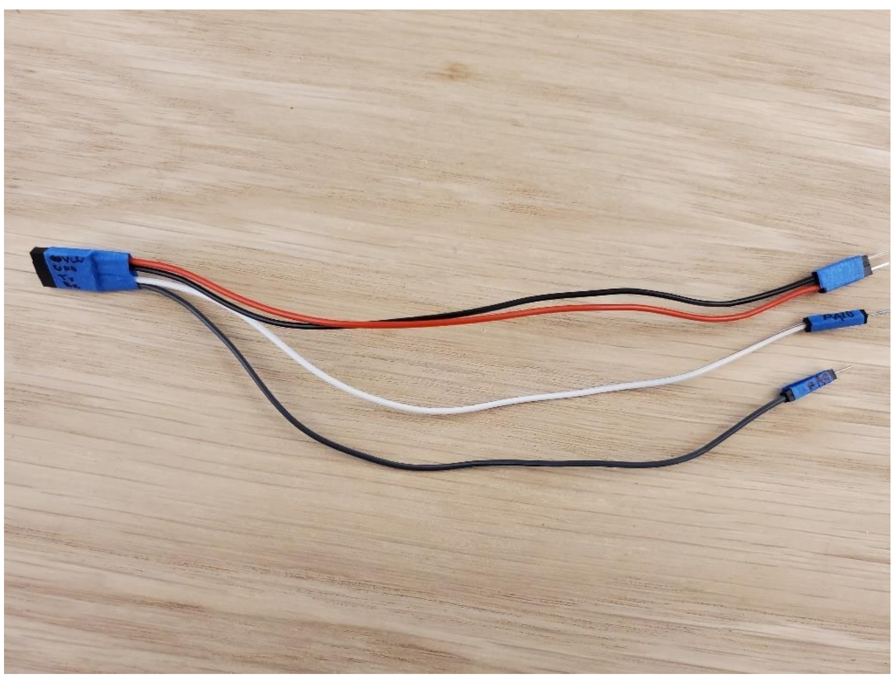
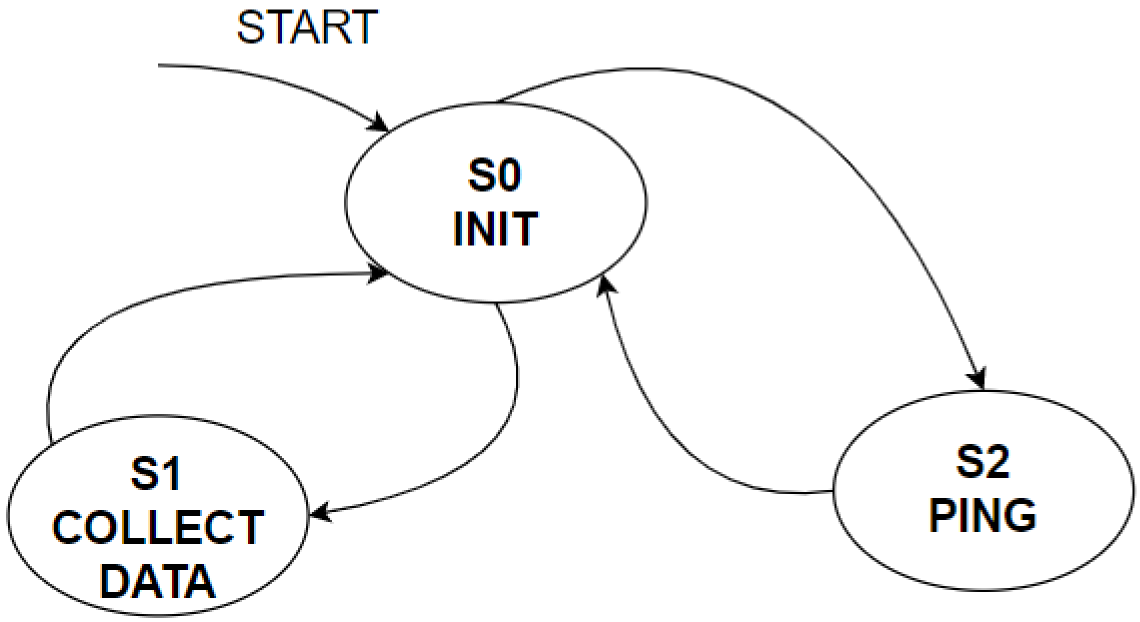


Figure 8: Bluetooth Cables. Connect labeled ends to corresponding pins. The female connectors should connect to the male pins adjacent to the HC05 module. Connect the labeled portions to the corresponding pins labeled in blue tape on the shield. The other ends should be connected to 5V, GND, D2 and D8 as necessary.

State Transition Diagram



The DAQ initializes in state 0 and waits there until a signal from the frontend is received. If the frontend sends a 'g' it will enter state 1 and begin data collection. It will stay there until it receives the signal to stop and reenter state 0. If from state 0, the DAQ receives a 'p' instead, the DAQ will enter state 2 and stay in ping mode until exiting.

State 0

Set up all variables. Upon transitioning to state 1, record timestamp to zero system.

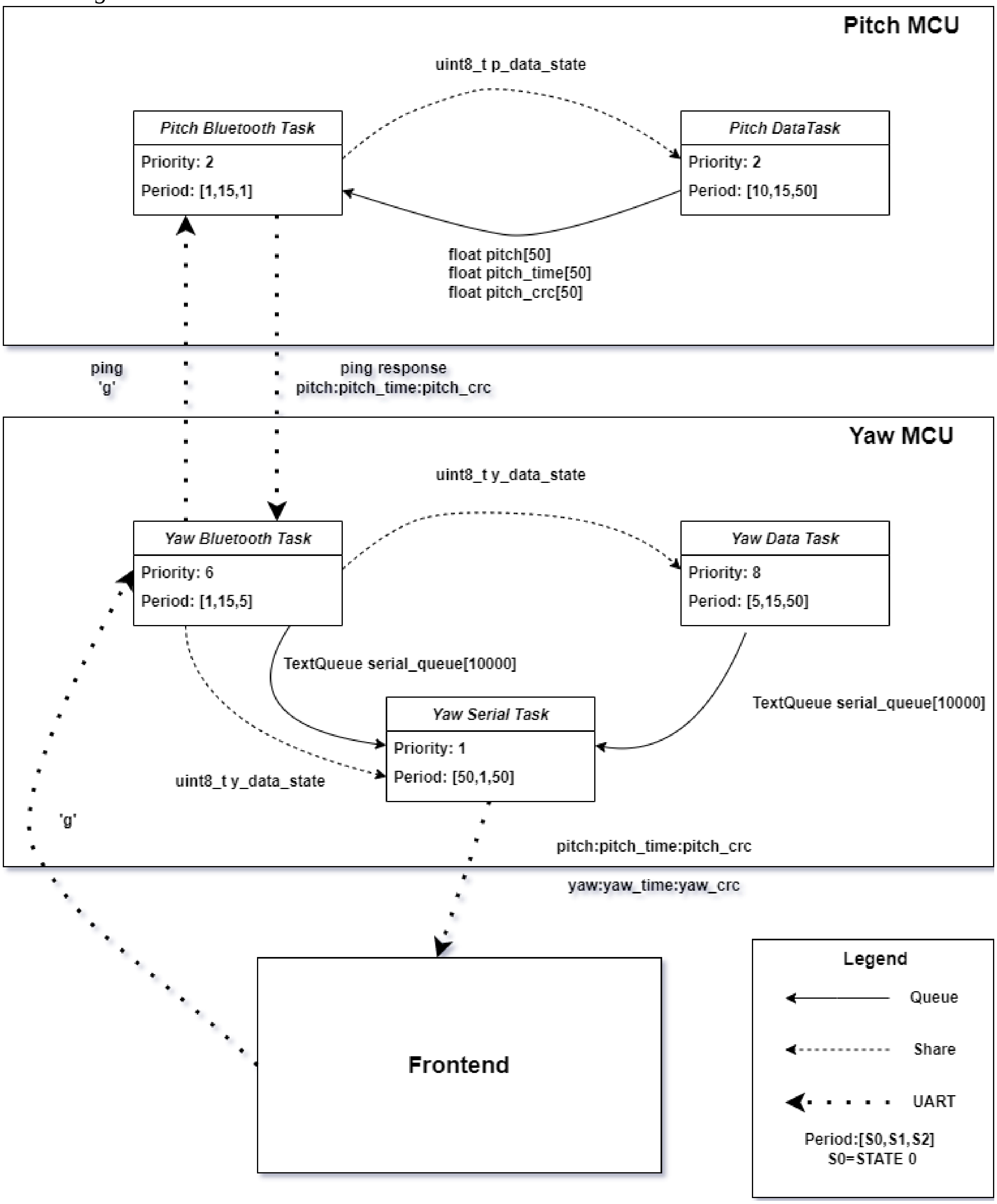
State 1

Record all data and send to the PC over serial communication.

State 2

Yaw MCU pings Pitch MCU every 250ms. Upon. receiving a ping, Pitch MCU sends Yaw MCU a ping response back

Task Diagram



Appendix X: Velocity Efficiency Verification Test

Test Goals:
Find the yaw and pitch mass moments of inertia and the center of mass of the planarizer. This inertia will be helpful in solving for the velocity efficiency and natural frequency of the planarizer.

Safety Concern	Mitigation
Swinging hazard	• User must stay out of the path of the boom while it is being swung so that it does not contact any part of their body
Dropping hazard	• User must hold base away from their head and extremities so that if it falls on accident, it does not contact any part of their body • User should wear closed toed shoes • User must be able to hold 5 lb base against the wall for at least half a minute

Test Safety ***& Equipment Required:***

- Full planarizer assembly except robot leg
- Video camera (phone will suffice)
- Tape measurer
- Colored sharpie
- Table to balance planarizer on
- Chair
- Three persons
- Dumbbell (or other shaft to balance boom on top of)
- Video editing software (Windows Movie Maker, Adobe Premiere, etc.)

*Test **Procedure:***

*Mass Moment of Inertia Determinati**on***

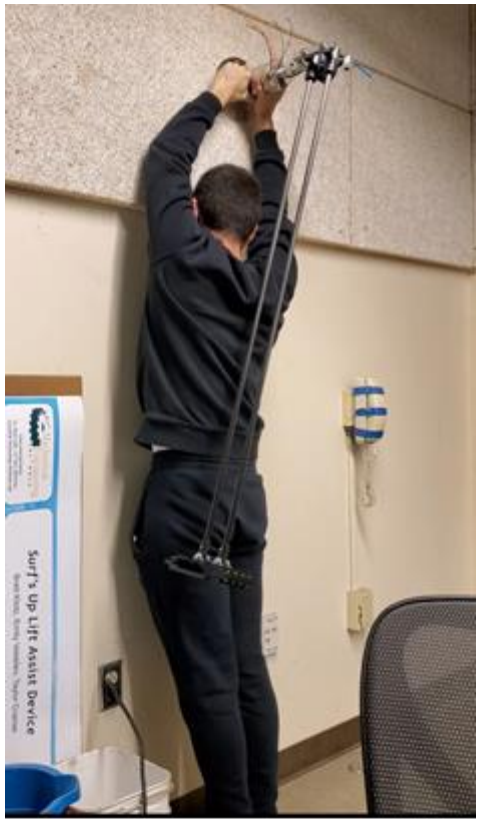


Figure 1: Yaw moment of inertia test

1. Verify all test participants are wearing proper safety equipment. These include closed toed shoes
2. To determine the yaw moment of inertia, one person should hold the base plate against a flat wall. One person will be releasing the boom at an angle that is approximately 45°. When the person releases the boom, they should step out of the way and allow the booms to swing like a pendulum.
3. Another person should be videoing this motion and should stop the video when the pendulum appears to stop and should be counting the amount of times the boom swung within its period back and forth. Record this number below.
4. The person recording should analyze the time from which the boom was released to when it appeared to stop using a video editing software for high accuracy. Record this time.
5. This recorded time is divided by the number of times that the pendulum swung to obtain the period. Record this number in Table 1 .
6. Repeat steps 2-5 for at least one more trial.

Figure 2: Pitch moment of inertia test

7. In order to compute the pitch mass moment of inertia, a person needs to hold the yoke flush against the ceiling or an upper door frame. A chair may be necessary to reach this height.
8. Another person should release the boom at approximately a 45° angle and allow it to swing about the pitch axis of the planarizer.
9. Repeat steps 3-6. Record in Table 2.

Table 1: Yaw Mass Moment of Inertia

Test	Time	# of Oscillations	Period (s)
1	12.61	6	2.106
2	21.08	10	2.108

Table 2: Pitch Mass Moment of Inertia

Test	Time	# of Oscillations	Period (s)
1	8.28	4	2.07
2	6.24	3	2.08

Center of ***Gravity Determination***

Figure 3: Center of gravity test

1. Place planarizer assembly (focusing on the boom assembly) onto a dumbbell (or shaft) placed onto a table. Move it along the boom until a point where it is balanced without anyone holding the assembly. Mark this point on the boom with a colored sharpie. Measure this point using a tape measurer relative to the center axis of the yoke and record this below in Table 3.

Table 3: Planarizer Center of Gravity

Center of Gravity Distance	9.25 inches

2. Use period from the yaw inertia test and the center of gravity distance to compute the yaw mass moment of inertia about the center of gravity as shown in EQ 1.

$$\bar{I} = \frac{mgr_{cg}}{(2\pi f)^2} - m{r_{cg}}^2$$

EQ 1

3. Repeat the process for computing the pitch mass moment of inertia. Record these values below in Table 4.

Table 4: Mass Moment of Inertia for both tests

Mass Moment of Inertia	Value
Yaw	1.011 lbf-ft^2
Pitch	0.695 lbf-ft^2

4. Compute the velocity efficiency based on EQ 2. Record this value below in

$$\eta_{vel} = \frac{v}{v_r} = \sqrt{\frac{m_r}{\frac{\bar{I}_b}{l_r^2} + \frac{m_b l_b^2}{4 l_r^2} + \frac{\bar{I_r}}{l_r^2} + m_r}}$$

EQ 2

5. Compute the natural frequency of the planarizer based on EQ 3. This utilizes the inertia and the Young's modulus determined from the deflection test. Record this value below in

$$\omega_n = \sqrt{\frac{315EI}{2m_b l^3}}$$

EQ 3

Table 5: Important Planarizer Dynamic Characteristics

Dynamic Characteristic	Value
Velocity Efficiency (η_{vel})	78.4%
Natural Frequency (ω_n)	0.476 Hz

Appendix Y: Deflection Test

Test Goals:
Statically load boom based off of 27 lb ground reaction force (applied moment changes based off of length of boom). Apply loads larger than this maximum expected value. Check for largest point of deflection. Note down any effects that may interfere with position calculations. Then, calculate Young's modulus of the boom.

*Test **Equipment Required:***

- Closed toed shoes
- 15 lb dumbbell
- 20 lb dumbbell
- 2x 48" Carbon fiber booms
- Height gauge
- 2x C-clamps
- 2x 1" Rollers (Aluminum Round Tube Stock)
- Rope (6-7 mm in diameter)
- Masking tape


Figure 53: Boom deflection testing setup

Test Safety:

Safety Concern	Mitigation
Heavy Weights (drop on toe, part of user's body)	• Tie tight double fisherman knot against the boom and the weight so that it does not fall out • Keep extremities away from boom area while loaded • Closed toed shoes
Pinching Points	• Avoid fingers when clamping booms down

Test ***Procedure:***

1. Verify all test participants are wearing proper safety equipment. These include closed toed shoes. See Test Safety section for additional details.
2. Place three tables next to each other as shown above in **Error! Reference source not found.**. The two end tables should be spaced far enough apart so that the boom can span across. There should be a middle table for the height gauge to mount onto. The tables should be high enough so that the dumbbells can dangle from the rope without touching the ground.
3. Place rollers on edge of end tables and clamp down to table using C-Clamps. The rollers should be constrained so that they cannot move.
4. Place carbon fiber boom onto rollers. Measure the distance from the center of the roller to the end of the boom. Mark this on the roller and place a piece of tape on the boom.
5. Once the distance from the center of the roller to the end of the boom is equidistant on both sides, the boom can be taped to the roller so that the boom maintains its position while being loaded.
6. Place height gauge on center table. Ensure that this table is flat and clear of any debris that could affect the flatness relation of the height gauge to the table. A Micro-Flat used as a center table is ideal.
7. Move the height gauge so that when it is lowered, it is aligned with the center of the boom. While the boom is unloaded, lower the height gauge until it contacts the surface of the boom. Record this position in Table 10.

Figure 54: Height gauge contacting boom surface

8. Measure the weights of the dumbbells using a bathroom scale. Record these weights.
9. Using rope, feed around boom and around 15 lb dumbbell and tie a secure knot. Ensure that there is tension in the rope between the boom and the weight so that the dumbbell is properly loading the boom. A double fisherman knot is recommended to prevent the weight from falling.
10. The boom will begin to slightly sag. At this point, record the height gauge reading. It should be lower than the initial reading.
11. Repeat steps 9 and 10 with the 20 lb dumbbell alone, and then the 20 lb dumbbell in series with the 15 lb dumbbell. When adding the 15 lb dumbbell in series, be sure to tie a loop in the rope for the lower dumbbell to hang from as shown above in **Error! Reference source not found.**.
12. Based on the deflection, compute the uncertainty percentage due to deflection based on the uncertainty analysis calculations computed for the data resolution of the entire planarizer.
13. Compute Young's modulus based on the 15 lb load using EQ 1. The variables are referenced in Figure 355.

Results:

Table 10: Deflection Test Data

Trial	Height Gauge Reading	Approximate Weight	Deflection (y_a)	Measured Weight	E Uncertainty %
1	1.5375	Unloaded	0		
2	1.052	15 lb	0.4855	16.06	26.63
3	0.929	20 lb	0.6085	20	21.32
4	0.490	35 lb	1.0475	36.06	12.56

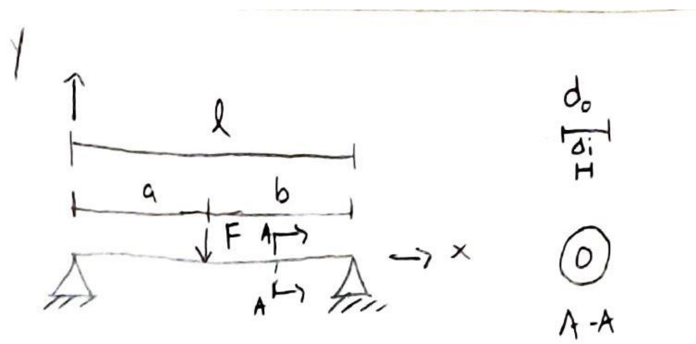


Figure 355: Reference figure for computing Young's modulus

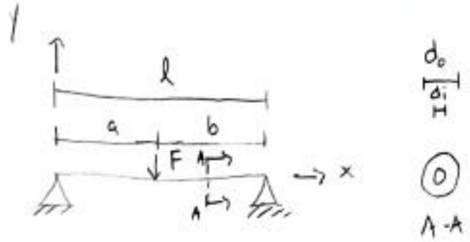
$$E = \frac{32(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a l({d_o}^4 - {d_i}^4)} \quad \text{EQ 1}$$

Analysis:

A primary motivation behind determining the Young's Modulus of the carbon boom is to calculate deflection and ultimately, the resolution we can expect out of the system. The following hand calculations show how we determine the uncertainty due to Young's Modulus as well as that resolution. It takes into account the uncertainty due to manufacturing tolerances and the uncertainty due to deflection.

3 Point Bend Test

1



Goal: determine stiffness, E

From Shigley's Mechanical Engineering Design, 11th ed.

deflection @ $x=a$ is given by

$$y_a = \frac{Fab}{6EIl}(a^2+b^2-l^2) \qquad \text{(Table A-9, pg 1031)}$$

where:

$$I = \frac{\pi}{64}(d_o^4-d_i^4) \Rightarrow y_a = \frac{Fa^3b + Fab^3 - Fabl^2}{6E\frac{\pi}{64}l(d_o^4-d_i^4)}$$

$$E = \frac{32(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a l (d_o^4-d_i^4)}$$

The uncertainty then is given by:

$$U_E = \sqrt{\left(\frac{\partial E}{\partial F}U_F\right)^2 + \left(\frac{\partial E}{\partial a}U_a\right)^2 + \left(\frac{\partial E}{\partial b}U_b\right)^2 + \left(\frac{\partial E}{\partial l}U_l\right)^2 + \left(\frac{\partial E}{\partial y_a}U_{y_a}\right)^2 + \left(\frac{\partial E}{\partial d_o}U_{d_o}\right)^2 + \left(\frac{\partial E}{\partial d_i}U_{d_i}\right)^2}$$

where:

$$\frac{\partial E}{\partial F} = \frac{32(a^3b + ab^3 - abl^2)}{3\pi y_a l(d_o^4-d_i^4)}$$

$$\frac{\partial E}{\partial a} = \frac{32(3Fa^2b + Fb^3 - Fbl^2)}{3\pi y_a l(d_o^4-d_i^4)}$$

$$\frac{\partial E}{\partial b} = \frac{32(Fa^3 + 3Fab^2 + Fal^2)}{3\pi y_a l(d_o^4-d_i^4)}$$

$$\frac{\partial E}{\partial l} = \frac{-32Fab(a^2+b^2-l^2)}{3\pi y_a l^2(d_o^4-d_i^4)}$$

$$\frac{\partial E}{\partial y_a} = \frac{-32(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a^2 l(d_o^4-d_i^4)}$$

$$\frac{\partial E}{\partial d_o} = \frac{-128d_o^3(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a l(d_o^4-d_i^4)^2}$$

$$\frac{\partial E}{\partial d_i} = \frac{128d_i^3(Fa^3b + Fab^3 - Fabl^2)}{3\pi y_a l(d_o^4-d_i^4)^2}$$

Additionally, U_b is derived from U_a & U_l:

$b = l - a$

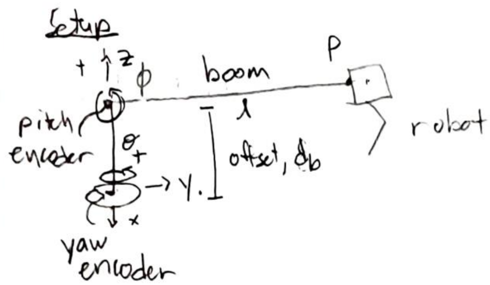
$$\hookrightarrow \quad U_b = \sqrt{\left(\frac{\partial b}{\partial l} U_l\right)^2 + \left(\frac{\partial b}{\partial a} U_a\right)^2}$$

$$= \sqrt{(1-a)^2 U_l^2 + (l-1)^2 U_a^2}$$

Data Resolution

The planarizer DAQ makes use of two encoders, and a roughly 4" carbon fiber boom. This calculation will take into account manufacturing tolerances, measurement uncertainty, and boom deflection

Setup

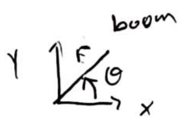


* coord system is fixed at base of planarizer

** The DAQ will only measure the position of the boom's end

Position Calculation

Top View



$$r = l\cos\phi$$

$$P_x = r\cos\theta = l\cos\theta\cos\phi$$

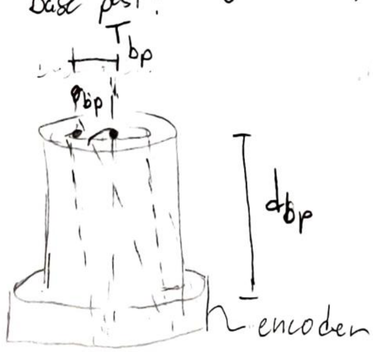
$$P_y = r\sin\theta = l\sin\theta\cos\phi$$

$$P_z = l\sin\phi + d_b$$

Tolerance Stackup

We are concerned with the concentricity between the encoders and the rods they measure as well as the perpendicularity between the yaw rod and the pitch rod and the perpendicularity between the boom and the pitch rod. Small angle approximation will be used.

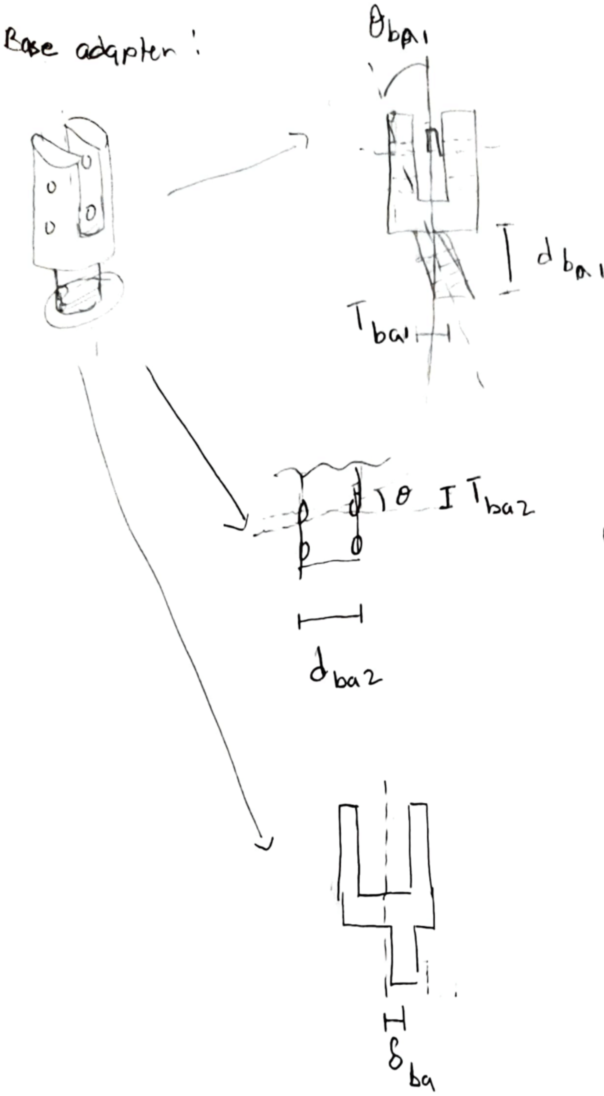
Base post:



$$\theta_{bp} = \tan^{-1}\left(\frac{T_{bp}}{d_{bp}}\right)$$

$$\theta_{bp} \approx \frac{T_{bp}}{d_{bp}} \quad \text{(worst case tolerance)}$$

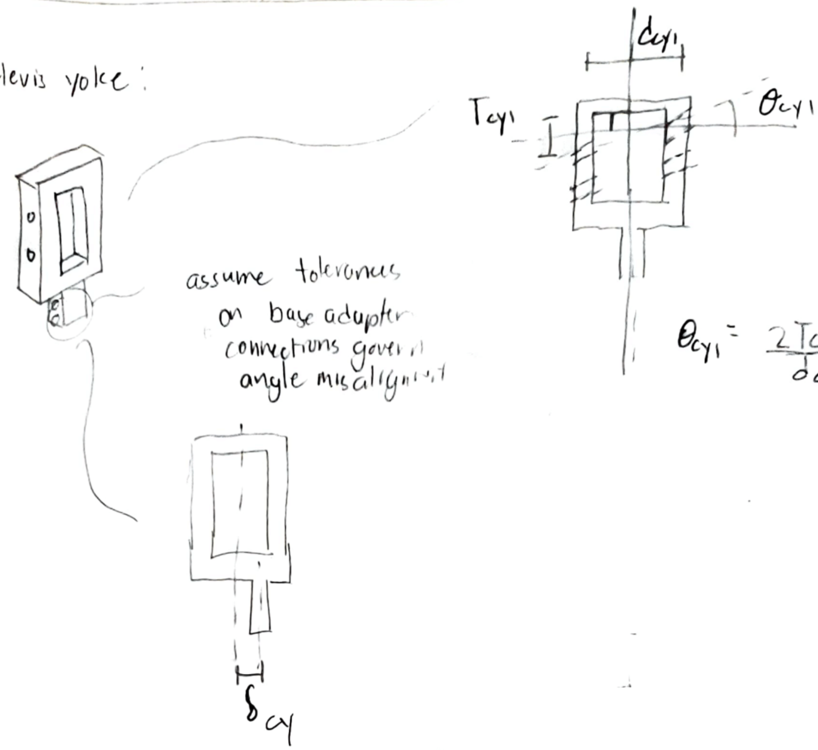
Base adapter:



$$\theta_{ba1} \approx \frac{T_{ba1}}{d_{ba1}}$$

$$\theta_{ba2} \approx \frac{T_{ba2}}{d_{ba2}}$$

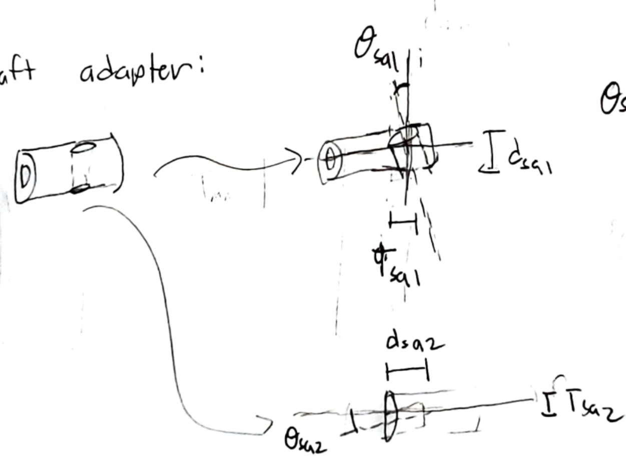
Clevis yoke:



assume tolerances on base adapter connections govern angle misalignment

$$\theta_{cy1} = \frac{2T_{cy1}}{d_{cy1}}$$

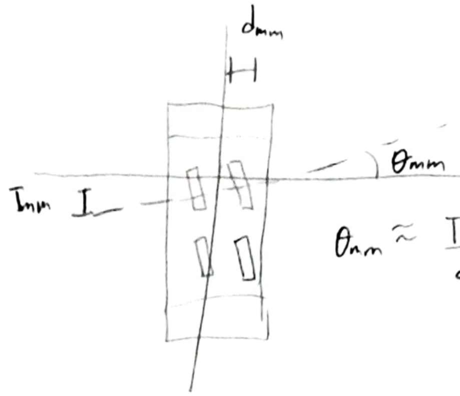
Shaft adapter:



$$\theta_{sa1} \approx \frac{T_{sa1}}{d_{sa1}}$$

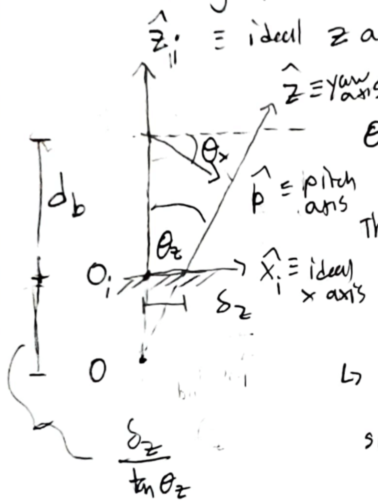
$$\theta_{sa2} \approx \frac{T_{sa2}}{d_{sa2}}$$

Main Mount:



$$\theta_{mm} \approx \frac{I_{mm}}{d_{mm}}$$

Manufacturing Tolerance stackups:



$$\theta_z = \sqrt{\theta_{bp}^2 + \theta_{ba_1}^2 + \theta_{ba_2}^2}$$

$$\theta_x = \sqrt{\theta_z^2 + \theta_{a_1}^2 + \theta_{sa_1}^2 + \theta_{a_2}^2}$$

The amount of correctly measured z, then is given by $\hat{z}_i \cdot \hat{z} = \cos\theta_z$

$$\theta = \theta_{meas} \cos\theta_z$$

$$\hookrightarrow U_\theta)_{tol} = \theta - \theta_{meas} = \theta_{meas}(1 - \cos\theta_z)$$

similarly:

$$U_\phi)_{tol} = \phi_{meas}(1 - \cos\theta_x)$$

The extra offset length added to l, due to δ_z is given by

$$\delta_l = \left(d_b + \frac{\delta_z}{\tan\theta_z}\right)\tan\theta_z = d_b \tan\theta_z + \delta_z$$

Then, $U_l)_{tol} = \delta_l = d_b \tan\theta_z + \delta_z$

Deflection:

We will conservatively consider the worst case deflection to be that of the max deflection derived in Appendix O: Vibrational Analysis

$$y_{max} = \frac{F_i l^3}{9\sqrt{3}EI}$$

$$I = 2\left(\frac{\pi}{64}(d_o^4 - d_i^4) + \frac{\pi}{4}(d_o^2 - d_i^2)r^2\right)$$

$$= \frac{\pi}{2}\left[\frac{1}{16}(d_o^4 - d_i^4) + (d_o^2 - d_i^2)r^2\right]$$

$$U_{y_{max}} = \sqrt{\left(\frac{\partial y_{max}}{\partial l}U_l\right)^2 + \left(\frac{\partial y_{max}}{\partial E}U_E\right)^2 + \left(\frac{\partial y_{max}}{\partial d_o}U_{d_o}\right)^2 + \left(\frac{\partial y_{max}}{\partial d_i}U_{d_i}\right)^2 + \left(\frac{\partial y_{max}}{\partial r}U_r\right)^2}$$

where:

$$\frac{\partial y_{max}}{\partial l} = \frac{-\sqrt{3}Fl^2}{9E\left(\frac{\pi(d_i^2 - d_o^2)r^2}{2} + \frac{\pi(d_i^4 - d_o^4)}{32}\right)}$$

$$\frac{\partial y_{max}}{\partial d_i} = \frac{-\sqrt{3}Fl^3\left(\frac{\pi d_i^3}{8} + \pi d_i r^2\right)}{27E\left(\frac{\pi(d_i^2 - d_o^2)r^2}{2} + \frac{\pi(d_i^4 - d_o^4)}{32}\right)^2}$$

$$\frac{\partial y_{max}}{\partial E} = \frac{-\sqrt{3}Fl^3}{27E^2\left(\frac{\pi(d_i^2 - d_o^2)r^2}{2} + \frac{\pi(d_i^4 - d_o^4)}{32}\right)}$$

$$\frac{\partial y_{max}}{\partial r} = \frac{\pi\sqrt{3}Fl^3 r(d_i^2 - d_o^2)}{27E\left(\frac{\pi(d_i^2 - d_o^2)r^2}{2} + \frac{\pi(d_i^4 - d_o^4)}{32}\right)^2}$$

$$\frac{\partial y_{max}}{\partial d_o} = \frac{-\sqrt{3}Fl^3\left(\pi\frac{d_o^3}{8} + \pi d_o r^2\right)}{27E\left(\frac{\pi(d_i^2 - d_o^2)r^2}{2} + \frac{\pi(d_i^4 - d_o^4)}{32}\right)^2}$$

What we're interested in from deflection is the uncertainty it induces on the P_x, P_y, and P_z readings. We will treat y_{max} as an uncertainty then and RSS it with the y_{max} uncertainty, yielding

$$U_{defl} = \sqrt{U_{y_{max}}^2 + y_{max}^2}$$

Uncertainty propagation

$$U_{px} = \sqrt{\left(\frac{\partial U_{px}}{\partial l} U_l\right)^2 + \left(\frac{\partial U_{px}}{\partial \theta} U_\theta\right)^2 + \left(\frac{\partial U_{px}}{\partial \phi} U_\phi\right)^2 + U_{defl}^2}$$

where

$$\frac{\partial U_{px}}{\partial \lambda} = \cos\theta\cos\phi \qquad \frac{\partial U_{px}}{\partial \phi} = -l\cos\theta\sin\phi$$

$$\frac{\partial U_{px}}{\partial \theta} = -l\sin\theta\cos\phi$$

$$U_{py} = \sqrt{\left(\frac{\partial U_{py}}{\partial l} U_l\right)^2 + \left(\frac{\partial U_{py}}{\partial \theta} U_\theta\right)^2 + \left(\frac{\partial U_{py}}{\partial \phi} U_\phi\right)^2 + U_{defl}^2}$$

where:

$$\frac{\partial U_{py}}{\partial \lambda} = \sin\theta\cos\phi \qquad \frac{\partial U_{py}}{\partial \phi} = -l\sin\theta\sin\phi$$

$$\frac{\partial U_{py}}{\partial \theta} = l\cos\theta\cos\phi$$

$$U_{pz} = \sqrt{\left(\frac{\partial U_{pz}}{\partial l} U_l\right)^2 + \left(\frac{\partial U_{pz}}{\partial \phi} U_\phi\right)^2 + \left(\frac{\partial U_{pz}}{\partial d_b} U_{db}\right)^2 + U_{defl}^2}$$

where:

$$\frac{\partial U_{pz}}{\partial \lambda} = \sin\phi \qquad \frac{\partial U_{pz}}{\partial d_b} = 1$$

$$\frac{\partial U_{pz}}{\partial \phi} = l\cos\phi$$

* Though only parts of U_l, U_ϕ, and U_θ have been calculated so far, the complete uncertainty including measurement uncertainty will be used when calculating the final uncertainty values U_{px}, U_{py}, and U_{pz}

Table 2: Calculated uncertainty of Planarizer system (excludes uncertainty due to DAQ data matching algorithm)

Px uncertainty						
Measurement	Unit	Description	Theoretically Measured Value	Uncertainty	dE/d	Contribution
L_r	in	length to robot	48.922	0.008660254	0.5	0.00001875
θ	rad	angle read by yaw encoder	0.785398163	0.000252193	24.461	3.80553E-05
ϕ	rad	angle read by pitch encoder	7.85E-01	0.000304049	2.45E+01	5.53139E-05
					Final value (in):	**0.037533907**
Py uncertainty						
Measurement	Unit	Description	Theoretically Measured Value	Uncertainty	dE/d	Contribution
L_r	in	length to robot	48.922	0.008660254	5.00E-01	0.00001875
θ	rad	angle read by yaw encoder	0.785398163	0.000252193	2.45E+01	3.80553E-05
ϕ	rad	angle read by pitch encoder	7.85E-01	3.04E-04	2.45E+01	5.53139E-05
					Final value (in):	**0.037533907**
Pz uncertainty						
Measurement	Unit	Description	Theoretically Measured Value	Uncertainty	dE/d	Contribution
L_r	in	length to robot	48.922	0.008660254	7.07E-01	0.0000375
ϕ	rad	angle read by pitch encoder	0.785398163	0.000304049	3.46E+01	0.000110628
db	in	double boom neutral axis to encoder	6.28E+00	7.07E-03	1.00E+00	0.00005
					Final value (in):	**0.038662679**

From Table 2, we can see that the expected uncertainty is about 0.039 in at the most which comes out to approximately 1mm. The majority of this value actually comes from the deflection of the boom, which under a 25 lbf load came out to 0.036 in. All uncertainties were combined using a root sum square method. In comparison to boom deflection, the manufacturing uncertainties only make up a small amount. Improvements in the capabilities of this system could best be made by improving the stiffness of the boom. It is important to note that this does not take into account the resolution due to the software capabilities. This is only the resolution based on the hardware capabilities.

Appendix Z: DAQ Test

Test Goals

Determine latency of Bluetooth connection. Make qualitative check of streaming functionality.

Test Safety

We do not anticipate that there will be safety concerns with this test.

Test Equipment Required

- PC
    - Frontend code here: https://github.com/malkstik/Planarizer-DAQ/tree/main/MATLAB%20Frontend
        - Download: KeyboardTesting.mlx, PlanarizerDAQFrontEnd.mlx, VirtualKeyCode.m, getAsyncKeyState.m, license.txt, user32.h
        - In MATLAB, download *MATLAB Support for MinGW-w64 C/C++ Compiler* Add-on
- Assembled Planarizer (robot leg not necessary)
- 2x HC-05 Bluetooth modules
- 2x Nucleo STM32 L476RG
- Oscilloscope

Test Procedure

14. Power on Pitch MCU and connect Yaw MCU to PC using a USB to mini USB cable. Ensure that all wires are properly connected. Refer to the wiring guide on how to setup the wires on the DAQ.
15. Double check that the HC-05 Bluetooth modules are paired to each other. An LED on each should blink twice and then turn off for two seconds periodically.
16. On the PC, open device manager and check for which COM port the Yaw MCU is connected to.
17. Open PlanarizerDAQFrontEnd.mlx
18. On line 1, check to make sure that the variable, COMport, is set to the COM port found in step (3). Change it if it is not.
19. Connect the oscilloscope to all four UART lines (D2 and D8 on both Nucleos). The ones of greatest interest are Tx on Yaw MCU and Rx on the Pitch MCU . An example of the wiring setup is in Figure 1.

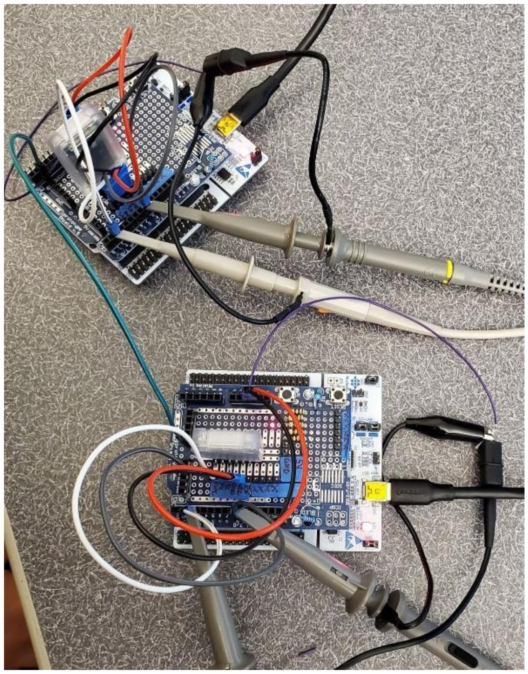


Figure 1: Wire connections. Both microcontrollers share common ground. Oscilloscope leads are connected to the Rx and Tx lines of both microcontrollers, in addition to ground.

20. Run the code and follow the directions provided in PlanarizerDAQFrontEnd.mlx to enter ping test mode. In ping mode, the Yaw MCU sends the character “i” to the Pitch MCU every 250 ms. Observing the Pitch MCU through the serial monitor should yield a series of “state: 2”, followed by four “i” lines. For this purpose, it is recommended that the Pitch MCU be powered by usb to laptop, as opposed to the power bank.
21. Adjust the oscilloscope as necessary until the high signals are easily visible.
22. Make note of the time it takes for all four UART lines to receive a signal in order of Pitch Tx, Yaw Rx, Yaw Tx, Pitch Rx. This can be used to compute the latency induced by the Bluetooth system. Do this for two different Bluetooth module distances, so that we may predict the latency at any distance.
23. You may now exit ping test mode and enter data collection mode
24. Once in data collection mode, manipulate the Planarizer and observe changes in the live-plot. Make note of any issues or areas for improvement.
25. Once satisfied, exit data collection mode. Some files should be generated containing the data taken during data collection

Test Results
This test was conducted in 192-118. On the Oscilloscope, we were looking for the ticks seen below in Figure 2.

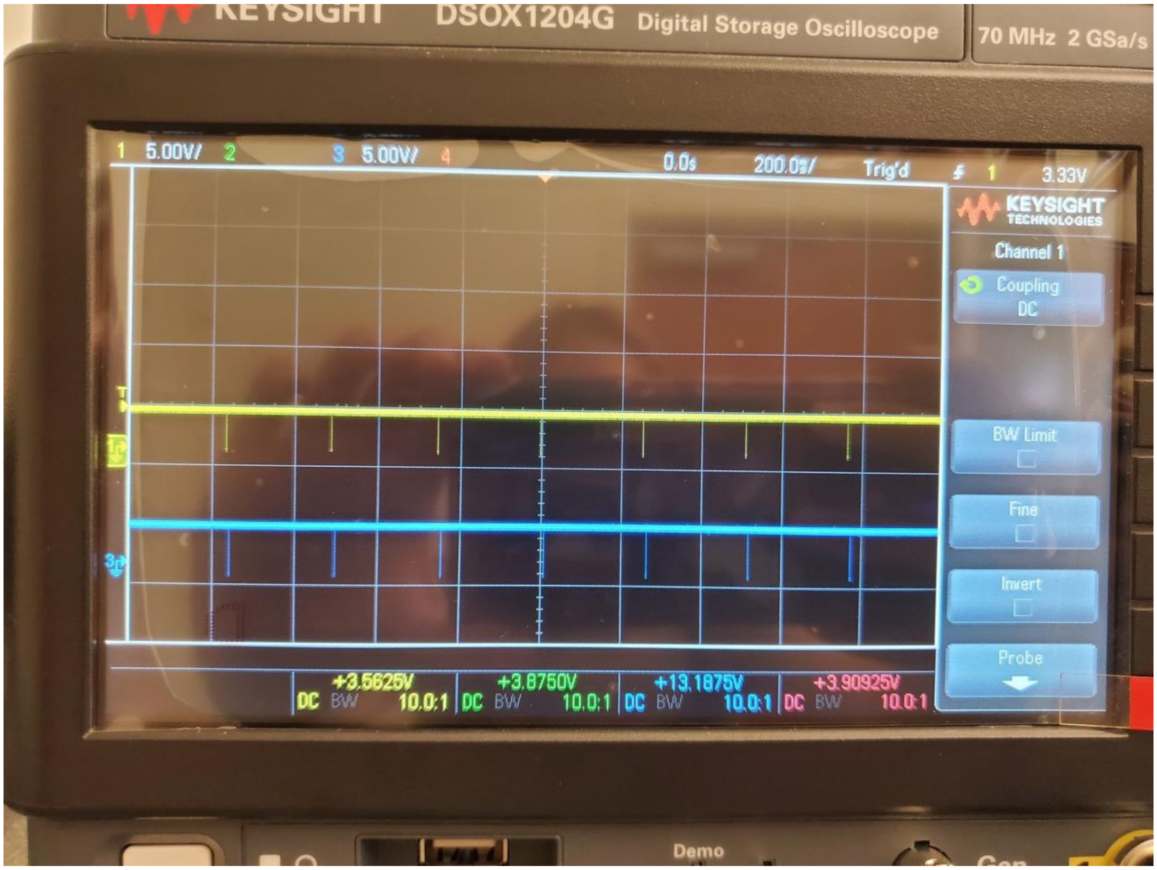


Figure 2. Binary ticks representing the signal sent from one bluetooth module to the other

Figures 3 and 4 show more zoomed in oscilloscope readings obtained for a Bluetooth module to Bluetooth module distance of 22 inches and 47.5 inches respectively.

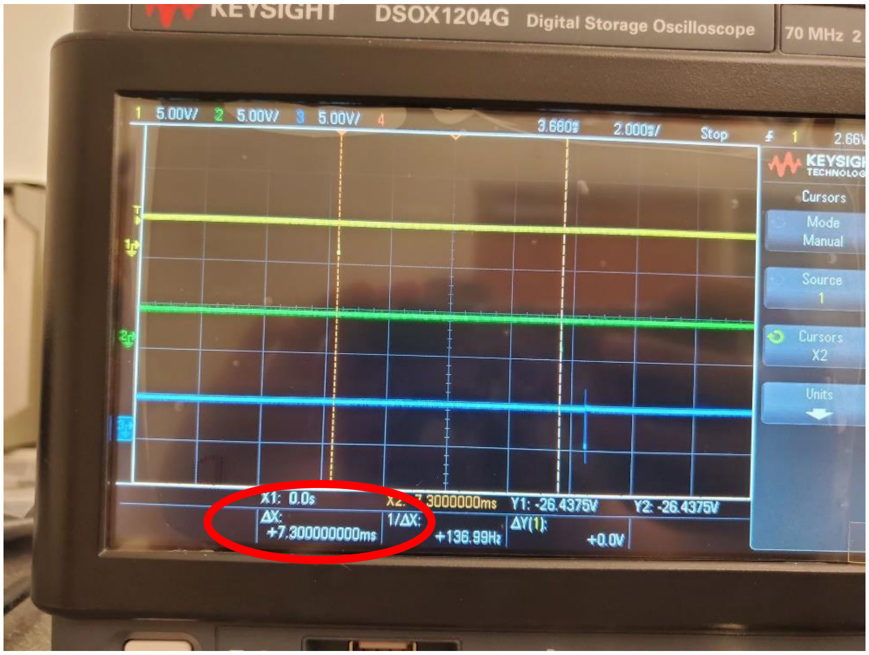


Figure 3: Bluetooth latency test at a module to module distance of 22 inches

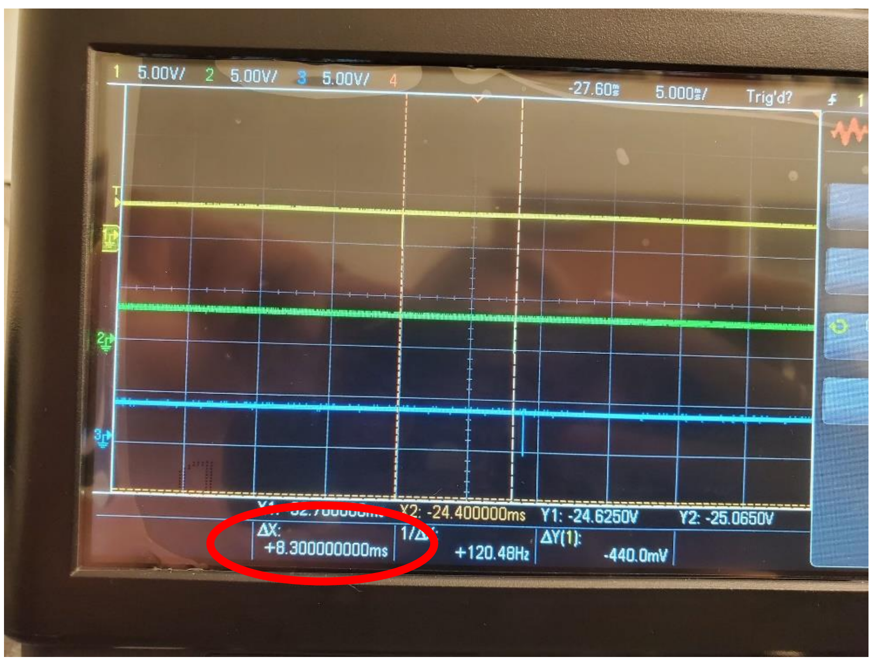


Figure 4: Bluetooth latency test at a module to module distance of 47.5 inches

Based off Figures 3 and 4, it was determined that the only data truly necessary was for the Tx signal coming from the Yaw MCU and the Rx signal coming from the Pitch MCU. This gives the time it takes for the signal to be sent from the yaw microcontroller, encoded and sent by the Yaw Bluetooth module, received by the Pitch Bluetooth modules, and finally sent to the pitch microcontroller. This is all we must account for, as we are most concerned with when the pitch microcontroller reacts to the yaw microcontroller' s signal to start data collection. The results are summarized om Table 1.

Table 1: Data taken from Bluetooth latency test

Yaw Tx to Pitch Rx (ms)	Module to Module (in)
7.3	22
8.3	47.5

Assuming that the distance between the modules is proportional to the time it takes to see a response on the pitch Rx line, we can generate a linear equation to predict Bluetooth latency. This is shown in Figure 5.

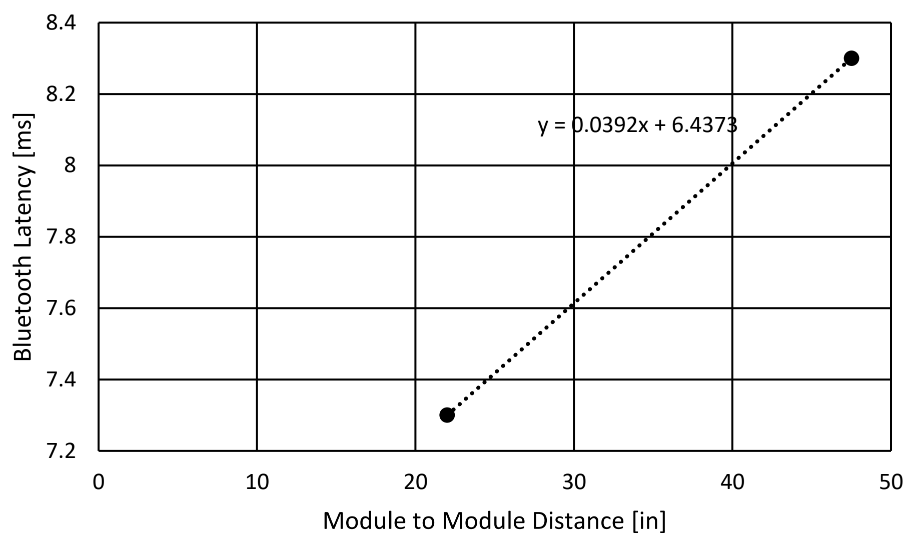


Figure 5: The Bluetooth latency is equivalent to 0.0392*l + 6.4373, where l is the distance between the Bluetooth modules

With an expected module to module distance of about 12 in for the DAQ, the Bluetooth latency should be roughly 6.9 ms.

With respect to the streaming functionality, the results are promising. Figure 6 below, shows the data from moving the planarizer as we expect the robot leg to.

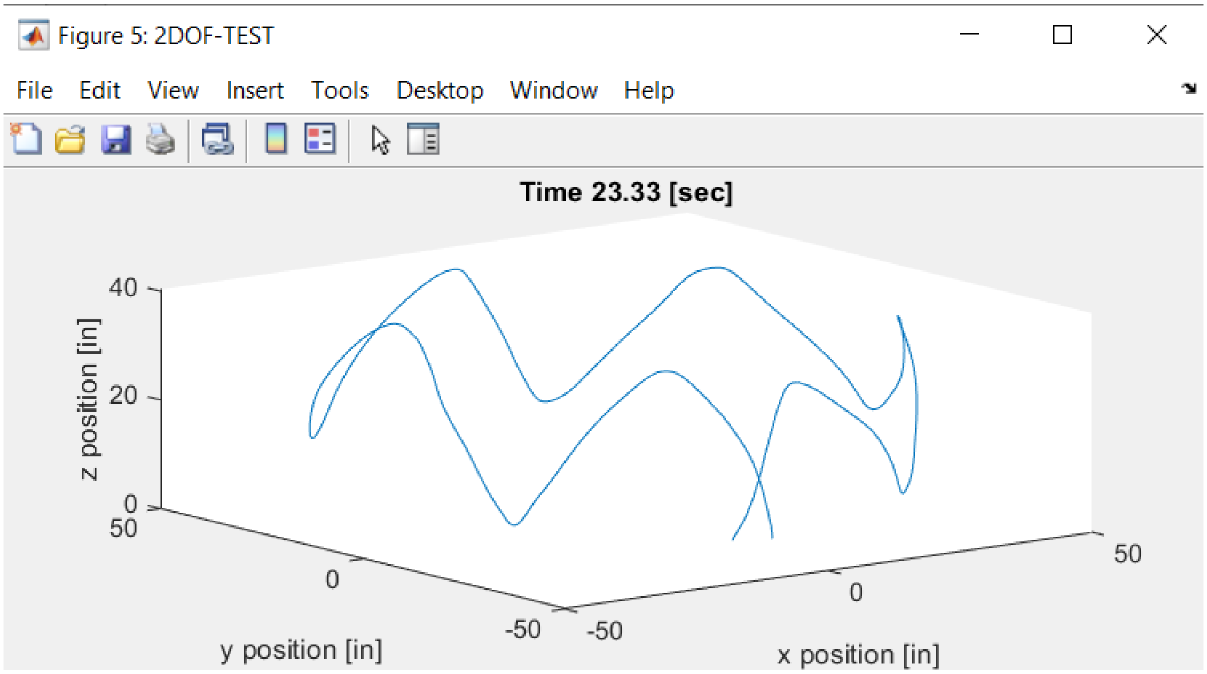
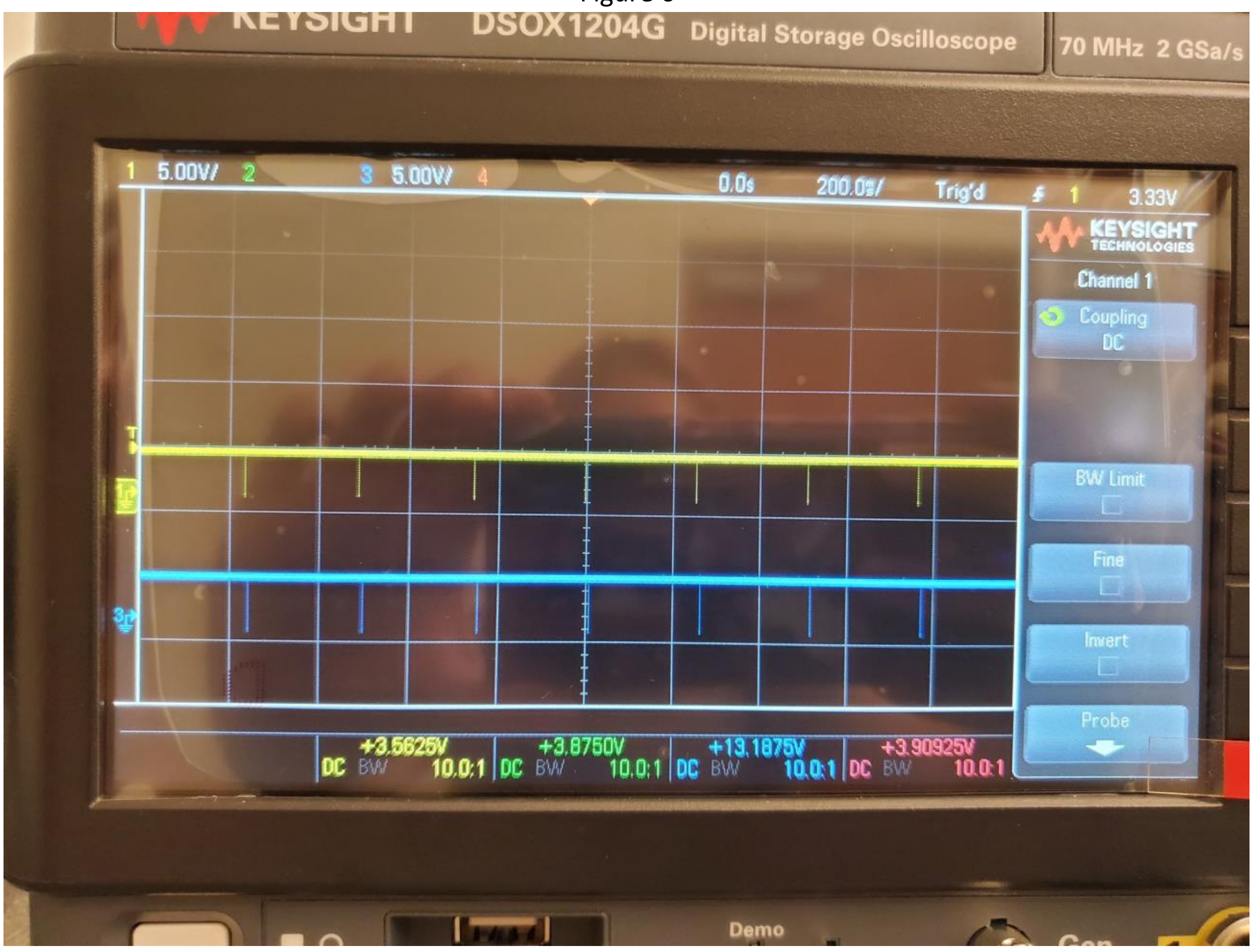


Figure 6



: Live-streamed plot of data from DAQ

The refresh rate of the plot was not smooth, but it felt usable. The time value keeps up well with real time, so we believe that the live streaming function works well. There were some times, however, where the time on the plot would zero out and not change. It is unclear what the reason was, as this seldom occurred. The issue is easily resolved by pressing the reset button on both MCUs, closing the serial port in MATLAB, and restarting the frontend code.

Discussion

Unfortunately, the Bluetooth latency is significantly higher than the 0.76ms delay we desired for trying to maintain a 1mm resolution combined with a 200Hz polling rate. This calculation was based off the max speed being 1.3 m/s. However, this latency may be factored into trying to match the data. We can delay the time that the yaw microcontroller zeros its timer. Given that task delays are configurable with 1 ms resolution, we would at best be able to get a latency of 0.1 ms, which is acceptable. A greater issue with the DAQ is that the data can only be matched within a 5ms interval, which leads to a 6.5mm error. With a greater polling rate we could match the data within smaller intervals.

Appendix A1: Operators' Manual

Planarizer User Manual

Complete Assembly: To complete our planarizer assembly, please build the base, yoke, and boom assemblies individually first.

Tools Required for Assembly:
Hand drill - for fastening nuts onto bolts
¼" socket – for fastening nuts onto 1/8" bolts
7/16" socket – for nuts and bolts mounting base plate to wood plank
7/64 hex key – for fastening 1/8" bolts
7/64 hex key for plastic shaft end set screw for boom
9/64 hex key for metal shaft end set screw for boom
5/32 hex key for clevis pin set screw
9/64 hex key for pin locking shaft collars
Screwdriver
Encoder assembly kit (centering tool, Allen key, spacer)

Base Assembly:

Base Plate Installation:

- To mount the base plate onto the plywood, insert the ¼ in screws along with the four 0.875" oversized washers through both the base plate holes and the plywood.

Figure 1. Plywood with drilled Holes

- Tighten ¼" nuts in the counterbore on the other side of plywood using a 7/16" socket.

Figure 2. Base Plate Bolted into to Plywood

Bottom Encoder Installation:

- Mount the encoder base on the bottom of the base assembly and around the shaft with two #4-40 mounting screws with the tapered side of the encoder base facing the open slot using a screwdriver.

Figure 3. Encoder Base Mounted under Base Enclosure

- To install the rest of the encoder, begin from step 2 of the US Digital Assembly instructions for installing an E6 encoder.

https://www.usdigital.com/media/j4rlqfmb/e6-assembly-instructions-for-shafts-greater- than-10.pdf

- Once the bottom encoder is secured around the shaft inside of the base enclosure, you may install the base enclosure by mounting it on the threads of the base plate.

Figure 4: Base Enclosure mounted onto Base Plate and Plywood

Boom Assembly:

- Mount four pillow bearings onto boom mount plate slots

Figure 5: Pillow bearings inserted into slots in boom mount plate

Fasten two 1/8” bolts to each of the four pillow bearings on the boom mount plate

- Secure these bolts with lock nuts by using a 1/4” socket or nut driver and 7/64” hex key.

Figure 6: Opposite side of boom mount plate with pillow bearings secured.

At this point, the robotic leg should be secured onto the leg mount plate, which is shown below.

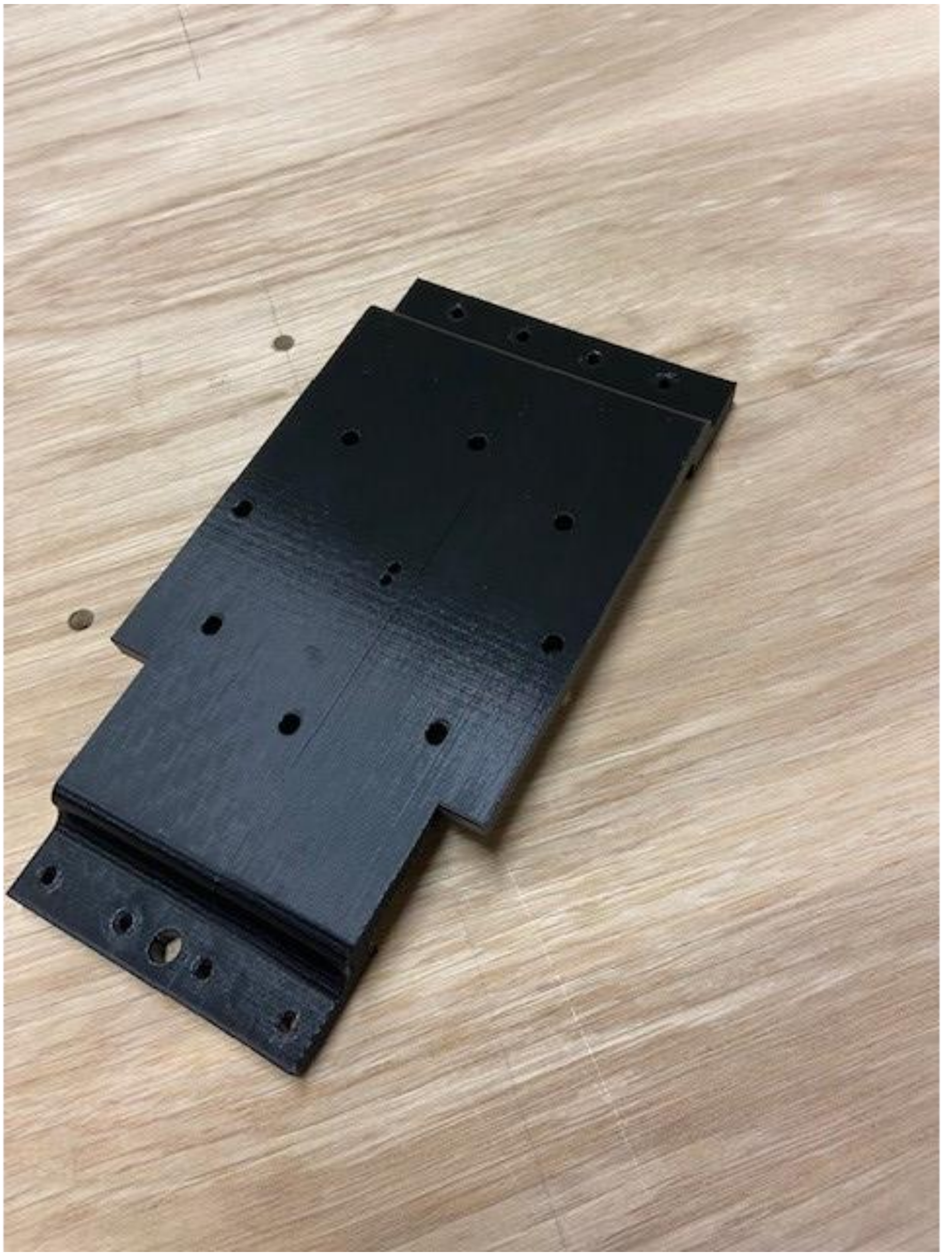


Figure 7: Outside of Leg Mount Plate

- The leg mount plate and the boom mount plate can now be joined to complete the leg mount assembly.
- Insert four 1/8” bolts through both the top and the bottom of the leg mount plate.

Figure 8: Top and Bottom View of Leg Mount Subassembly

- Fasten the two leg plates together using eight 1/8” bolts and lock nuts, with four on the top and bottom of each plate.

Gimbal Assembly

Components of Gimbal Assembly:

Figure 9: Aluminum Yoke

Figure 10: Metal Machined Shaft End with Set Screw

Figure 11: Ring Shims

Figure 12: Shaft Collars

Figure 13: Clevis Pin

Figure 14: Gimbal Assembly

- To assemble the yoke, stick the clevis pin through the side of the yoke along with the following components:
    1. Pin Locking Shaft Collar
    2. Ring Shim
    3. Metal Machined Shaft End (Make sure the end with the set screw installed is facing towards the threaded portion of the DAQ mount holes.
    4. Ring Shim
    5. Pin Locking Shaft Collar

- Make sure not to tighten each of the Pin Locking Shaft Collars completely around the clevis pin, as it will not allow the pin to spin completely free.
- Once parts are installed on each clevis pin, tighten the set screw in the metal machined shaft end with a 9/64” hex key to the clevis pin.

Figure 15: Encoder Mounting Holes on Side of Yoke

- Repeat this process for the bottom clevis pin. In this step, make sure that the clevis pin is installed in a way the head of the clevis pin is NOT on the same side as the encoder mounting holes in the side of the yoke.

Figure 16. Encoder Mounted to Yoke

- Install the second US Digital E6 Optical Encoder using [https://www.usdigital.com/media/j4rlqfmb/e6-assembly-instructions-for- shafts-greater- than-10.pdf](https://www.usdigital.com/media/j4rlqfmb/e6-assembly-instructions-for-shafts-greater-than-10.pdf) in the encoder mount holes in the side of the yoke with the tapered side of the encoder facing the back of the yoke, along with the set screws of the machined shaft ends and the threaded DAQ mount holes.
- **MAKE SURE NOT TO LOOSEN THE SET SCREW ON THE SHAFT END AND MOVE THE CLEVIS PIN WHILE THE ENCODER IS STILL INSTALLED.**

Boom Assembly

Figure 17: Plastic Shaft End

- Insert a plastic shaft end into each end of the carbon fiber booms and tighten the set screws onto the carbon fiber booms using a 7/64" hex key.

Figure 18: Shaft End mounted onto carbon fiber boom

Connect Subassemblies

- To connect the leg mount and boom assemblies, place the carbon fiber booms between the two pillow bearings and ensure the tab from the shaft end is inserted into the slot in the boom mount plate.

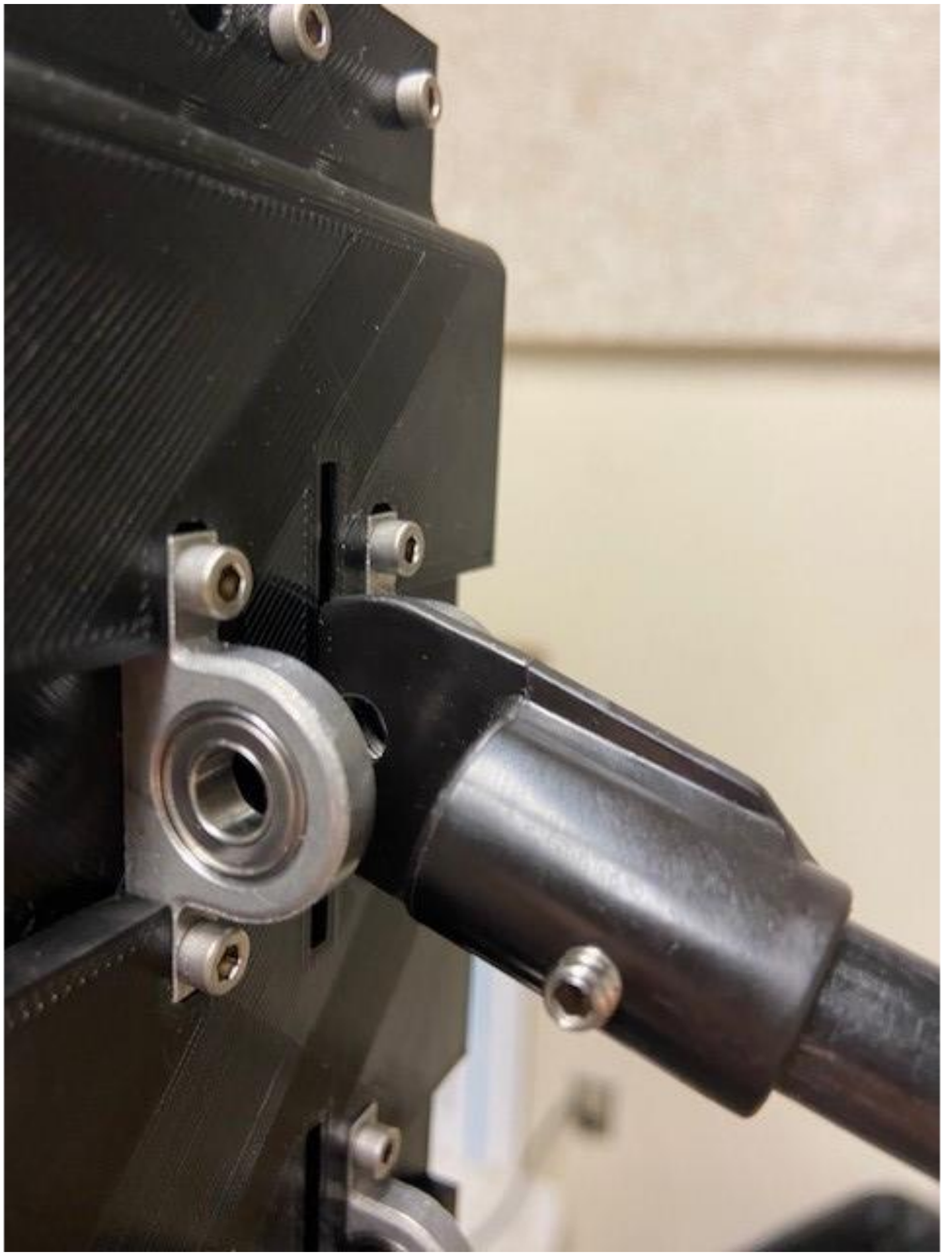


Figure 19: Boom inserted into Leg Mount Tab

- insert a 2” ¼”-20 hex bolt through both pillow bearings and through the hole in the plastic shaft end along with two plastic spacers between the two bearings.

Figure 20: Boom Secured into Leg Mount

- Secure the 2” bolt using a ¼-20” lock nut. Tighten the lock nut around the bolt with a 7/16” socket.

Base-Yoke Assembly:

- To connect the base and yoke subassemblies, insert the yoke into the slot on top of the base assembly

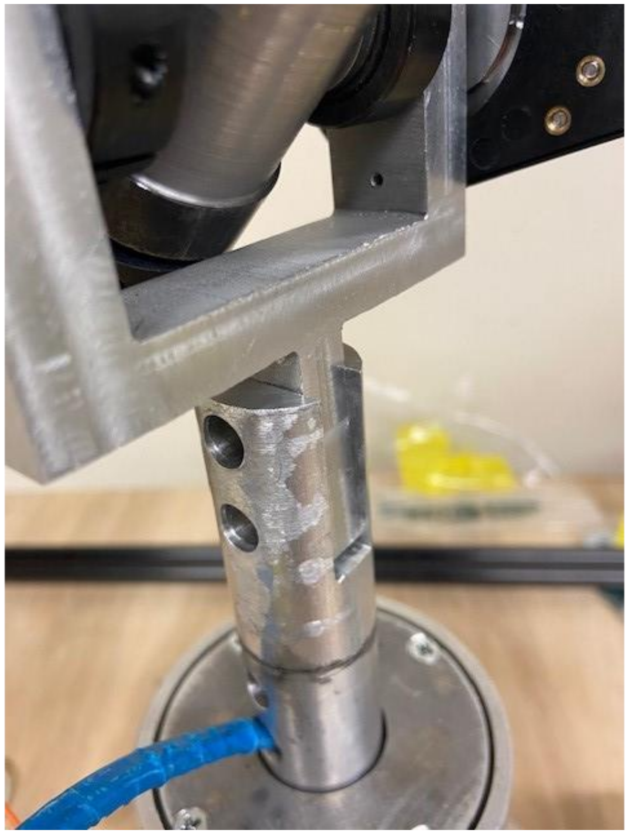


Figure 21: Yoke Assembly connected to Base Assembly

- Once the yoke is inserted, align the holes, and insert a ½” shoulder bolt in each of the holes.
- Once the shoulder bolts are inserted, secure them using a ¼”-20 nut on the end of each of the bolts.

Boom-Yoke Assembly

Figure 22: Carbon Fiber Booms secured into Metal Shaft Ends

- Insert each carbon fiber boom completely into the metal shaft end and tighten the set screws with a 9/64" Hex Screw.

DAQ Mount:

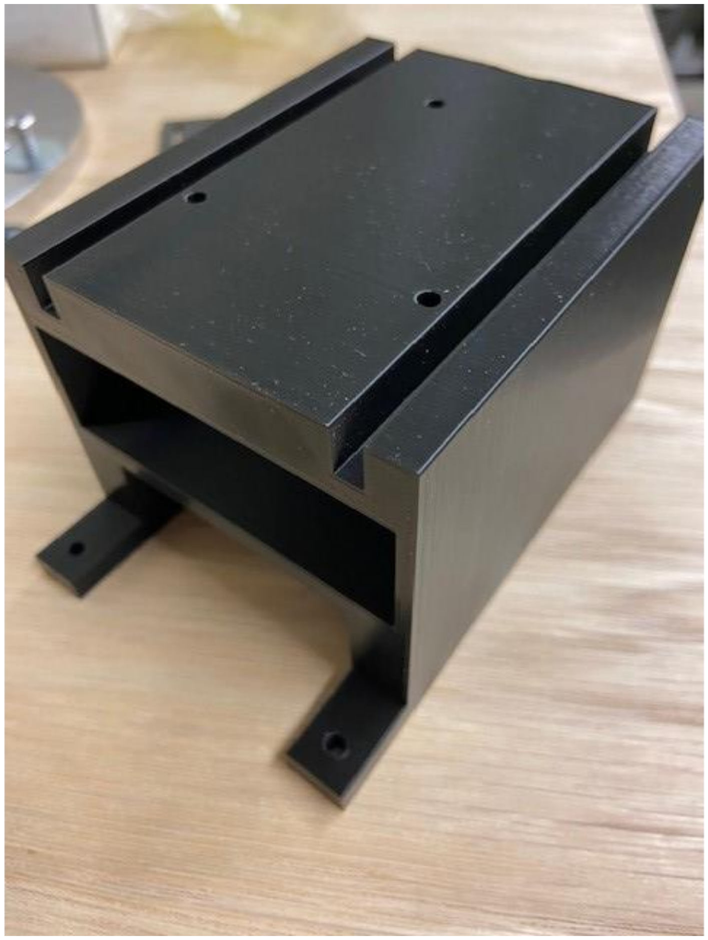


Figure 23: DAQ Mount

- To attach the DAQ mount to the Yoke Assembly, use two 1/8" bolts and insert them through both the DAQ mount and the threaded holes in the yoke. Tighten these bolts using a 7/64" hex key.

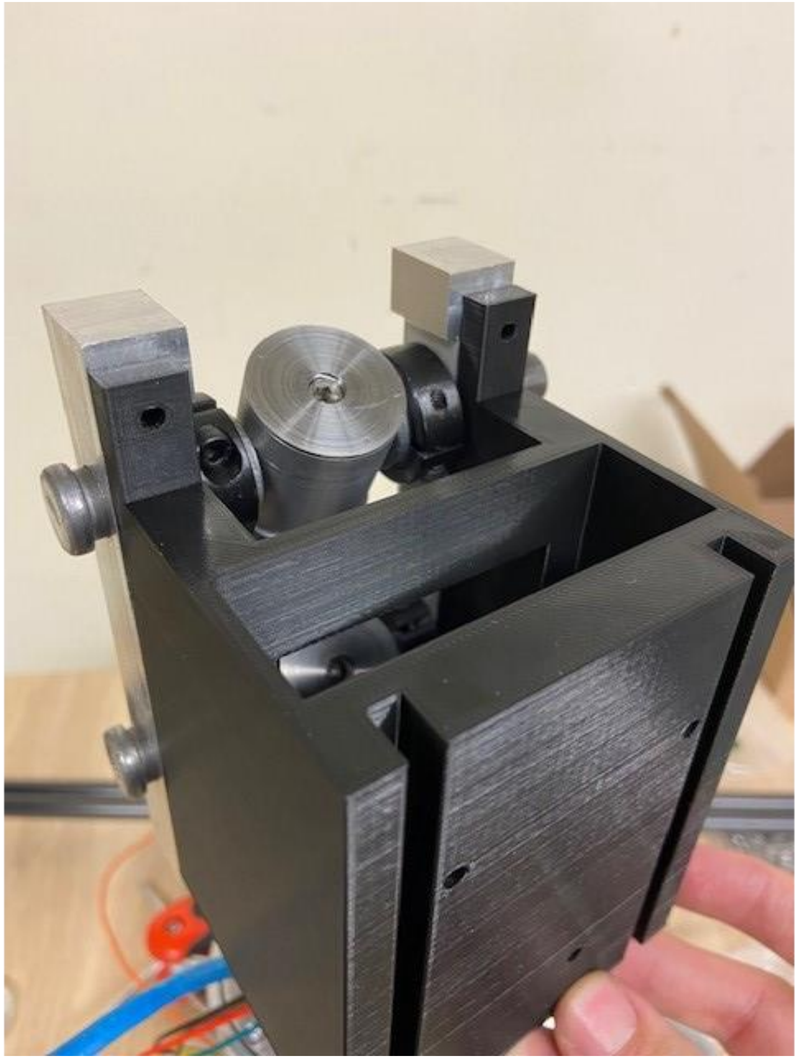


Figure 24: DAQ Mount mounted onto Yoke Subassembly